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THE LACCOLITHIC SERIES

O. T. JONES AND W. J. PUGH

ABSTRACT. The paper refers to recent work on albite dolerites in an Ordovician area between Builth and Llandrindod, Central Wales. Near Llandrindod an intrusion formerly mapped as a single dolerite has been proved to consist of 315 separate intrusions each surrounded by Lower Ordovician shales. Most of these are small bodies of mushroom form, and exposures of two of them in quarries show that they were fed along narrow pipe-like channels or stalks at right angles to their bases. The form of the space within which these intrusions are contained is similar to an asymmetrical laccolith. At Welfield near Builth dolerites are intruded as thin interrupted sheets at many different levels in shales; most are of flat mushroom form, but some are wing-like prolongations from short wide masses which are interpreted as feeders. Some very small subcircular intrusions may be feeders like those at Llandrindod. Here also the general form of the intrusive complex is that of a laccolith which shows certain resemblances to a cedar-tree laccolith. In the Western United States intrusions have been described which are transitional between the Welsh examples and Gilbert's ideal laccolith, and the authors regard all these as forms in a laccolithic series, individual examples being distinguished by their internal structure and relative amounts of igneous rock and sediments. Some remarks are made concerning Hunt's recent criticism of Gilbert's ideal laccolith.

INTRODUCTION

THE laccolith was first recognized as an important intrusive body about 70 years ago by Gilbert (1877). The typical laccolith of the Henry Mountains is a dome-shaped mass of igneous rock intruded into horizontally disposed sedimentary rocks, which are arched up by the intrusion, but the base of the intrusion is believed to be flat. An essential feature of this type of intrusion is that the sedimentary cover of the laccolith at any given point is arched by an amount which is equal to the thickness of the igneous rock below that point. Gilbert estimated that the sedimentary rocks which formed the arched cover of the laccoliths may have been from 7,000 to 11,000 feet in thickness and he believed that a considerable thickness of cover was necessary for intrusions to assume a laccolithic form.

A thin stalk at the base represents the igneous rock which congealed in the channel up which the magma travelled

through the underlying strata. The rocks below the base of the intrusion retained their horizontal disposition and were unaffected except for the rupture through them of the channel which is now represented by the stalk. It has been said that the stalk was an invention of the artist-geologist, W. H. Holmes. Some years ago, one of us (O.T.J.) during a visit to Holmes at his Washington office took the opportunity of asking him if that was in fact the case. He said he thought something of the kind was required in order to provide a channel for the magma. No such structure has ever been seen in any of the Henry Mountains laccoliths, nor, so far as we know until recently, in any other comparable intrusive forms.

Gilbert recognized that there might be various kinds of laccoliths which departed from his ideal form. He interpreted some igneous masses as compound laccoliths, made of two or more intrusions, situated so close together that the arching of the sediments was due to the combined effect of the intrusions. Another modification commonly occurred where several discontinuous thin sheet intrusions were interleaved with sediments in the lower part of the cover. He also suggested that an intrusive mass, conforming more or less closely to the simple ideal form, might include within it a certain amount of sedimentary rock.

It was not long before other intrusive masses, which conformed more or less to the ideal form yet showing departures from it of various kinds, were recognized elsewhere in the United States of America and other parts of the world with the result that the concept of the laccolith gained world-wide acceptance. Recently there has been an attempt to cast doubt upon Gilbert's simple interpretation of the intrusions of the Henry Mountains and a new interpretation has been proposed by Mr. C. B. Hunt (1942) which differs in essential features from that of Gilbert; some comments are offered later upon this interpretation.

It may be recalled that the Henry Mountains are situated in a relatively stable region of the earth's crust and when the laccoliths were intruded the sediments were on the whole disposed in horizontal layers. Such a region is in strong contrast with the geosynclinal regions of the Cordilleras to the west or of the Appalachians to the east. Certain types of

igneous activity appear to be closely associated with stable regions; other types are believed to be related to geosynclinal conditions and yet others to tectonically active regions. This aspect of the subject has been well discussed by Harker (1909) and others.

The work upon which we have been engaged during the past ten years in Central Wales appears to throw new light upon the structure of laccolithic bodies.

THE BUILTH-LLANDRINDOD ORDOVICIAN INLIER

The area which we have investigated is an inlier of Ordovician rocks occupying about 40 square miles and surrounded by unconformably overlying Silurian strata. We have mapped it on the scale of 1:2500 or approximately 25 inches to the mile.

The Ordovician rocks of the inlier and a nearby area consist in large part of dark shales, which can be sub-divided into five graptolite zones, namely, in descending order, *Dicranograptus*, *Nemagraptus gracilis*, *Glyptograptus teretiusculus*, *Didymograptus murchisoni* and *D. bifidus*. The first-named belongs to the Lower Bala, the next two to the Llandeilo and the last two to the Llanvirn, while in the area just outside the inlier Upper Bala grey mudstones also emerge from beneath the Silurian cover.

The base of the Ordovician is not seen in the inlier but by comparison with other areas it is inferred that the Llanvirn is underlain by the Arenig Series, mainly shales, and that series by the Cambrian System consisting probably of shales and sandstones or quartzites, which may be assumed to rest unconformably upon pre-Cambrian rocks. The thickness of rocks actually exposed up to the top of the Lower Bala varies from about 8,000 to 10,000 feet; it is estimated that the total thickness of sedimentary rocks from the base of the Cambrian to the top of the Lower Bala is about 16,000 feet and that they are mainly argillaceous sediments.

In one part of the inlier there is an important development of volcanic rocks, principally of spilitic and keratophyric types; these occur in the zone of *Didymorgraptus murchisoni*. In addition, several hundred intrusions of keratophyres and albite-dolerites occur, each of which is confined to certain restricted horizons in the shales.

The Ordovician rocks up to the end of the Lower Bala period were apparently little affected by earth movements, but after that they were subjected to powerful movements of various types. These latter movements were certainly completed before the Silurian (Upper Llandovery) rocks were laid down and there is reason to believe that they had at least begun and may have been largely completed before the deposition of the Upper Bala rocks. The intrusions, including even those which occur in the Lower Bala (*Dicranograptus* shales), had already been emplaced before these movements began and we believe that the intrusive activity was in some way related to the onset of these movements.

Throughout the early part of the Ordovician the inlier was a relatively stable region and had probably been so from Pre-Cambrian times onwards, but some miles to the west lay the Welsh geosyncline, the history of which has been described by one of us (O.T.J.). We believe that, prior to the intrusive episode which is described below, the stable region, probably extended for many miles to the east.

We have recently described two igneous complexes within the inlier which are characterized by numerous intrusions of albite-dolerite into Llandeilo shales. One of these is at the northern end of the inlier near Llandrindod Wells or Llandrindod as it is commonly called (1948,a); the other is at the southern end at Welfield about 7 miles south of Llandrindod and near Builth Wells, or more shortly, Builth (1946).

LLANDRINDOD COMPLEX

The old one-inch Geological Survey map which was published in 1850 shows a triangular mass of "greenstone" near Llandrindod. We have found that a large proportion of the area so mapped consists in fact of shales into which have been intruded numerous separate masses of dolerite. If an envelope line is drawn so as to enclose the masses which we have mapped, its course is closely similar to the boundary of the "greenstone" as shown on the Geological Survey map. The dolerites are intruded into shales of the *Nemagraptus gracilis* zone and as a result of subsequent earth-movements the rocks have been tilted in a general north-westerly direction at about 40°.

We found that the "greenstone," far from being one continuous mass, consists of no less than 315 separate masses, each separated from the other by shales (fig. 1). Approxi-

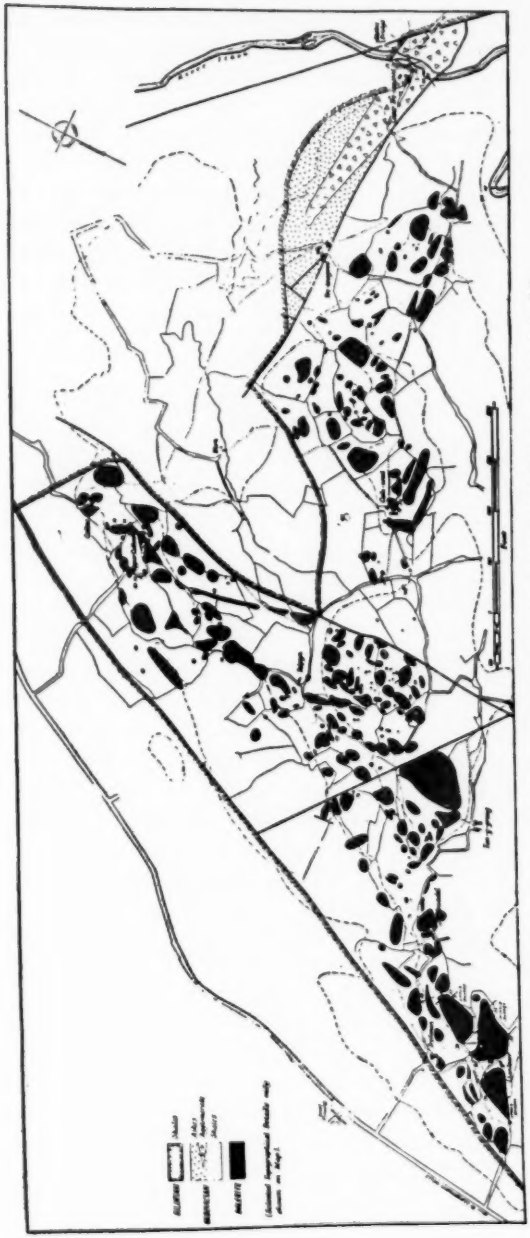

Fig. 1. Map of dolerite complex near Llandrindod (dolerite masses black).

mately two-thirds of this number are oval or ovoid, but occasionally some are of more irregular form. Several of the individual dolerites have been quarried and their relation to the shales by which they are surrounded can be clearly seen. Quarry sections show that the bases of the ovoid masses are conformable to the shales below them and that each was emplaced in the shales in such a way that, while the base was relatively flat, the overlying shales were raised above the base by an amount which was proportional to the thickness of the intrusion. Each of these masses has, therefore, the form of an ideal laccolith but on a very small scale.

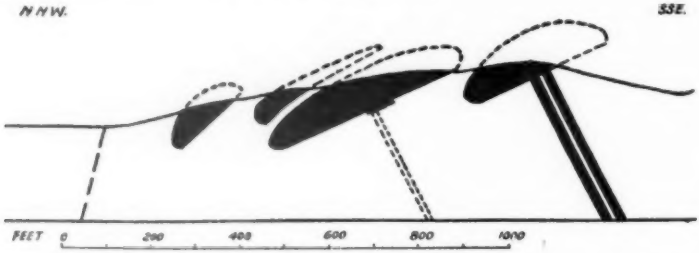

Fig. 2. Section through dolerite masses at Llanfawr quarries, near Llandrindod.

Three large quarries have been worked at the southwestern end of the area near Llanfawr. The dolerite in the middle quarry is 600 feet long and has a maximum width of 300 feet. Quarrying operations have removed the igneous rock from above the shales for a distance of 120 yards and in doing so have uncovered two small masses of dolerite about 55 to 35 feet long by 18 to 16 feet wide, which project through at right angles to the dip of the shales, on which the quarried dolerite formerly rested. Before the shales were tilted, these small dolerite masses were therefore vertical plug-like bodies; we were informed by the quarry foreman that they were joined to the base of the main dolerite and there seems to be no doubt that they were feeders to the masses above them (fig. 2).

When we first visited the upper quarry at Llanfawr there was visible at the northern end of the quarry a narrow bar of dolerite which projected downwards at right angles to the base of the main dolerite and reached the level of the quarry floor. When the lower end of this bar was exposed by excavation, it was found to end downwards in a sill about two

feet thick. We were informed that it was first encountered about 30 feet back from the quarry face and its dimensions were therefore about 30 feet by 7 feet or rather more. Although its connection with the main mass was proved, one cannot say that it continued downwards below the thin sill, but it is not improbable that it did so (fig. 2). It is regrettable that this plug has now been largely quarried away but we were fortunately able to secure a photograph of it before it was removed, which is reproduced as a plate in our description of this area (1948, a, pl IV, fig. 2).

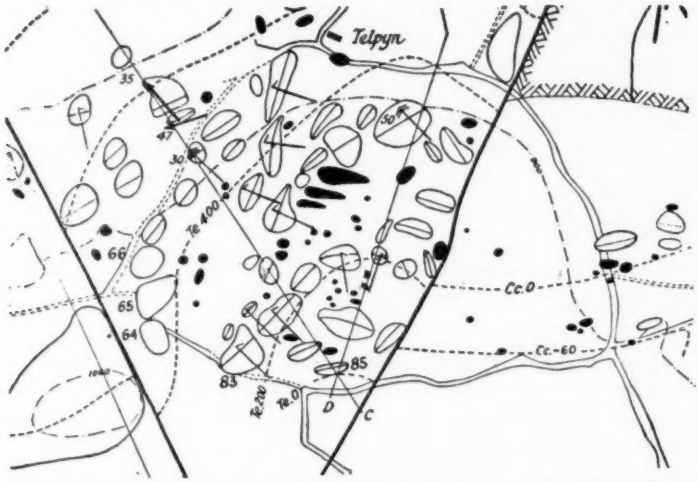

Fig. 3. Map of part of Llandrindod laccolith showing concordant dolerite masses (outline) and feeders (black). Straight lines within dolerite outcrop areas indicate direction of elongation of dolerite outcrops. Single-headed arrow—dip of sedimentary rocks. Double-headed arrow—dip of platy jointing in dolerite. Single-barbed arrow—dip of dolerite mass as inferred from slope of ground. Dashed line—approximate strike lines (in feet; Te.—Telpyn block, Cc.—Cefn-coed block).

Reproduced from part of Plate VI, Quart. Jour. Geol. Soc., **104**, 1948, with permission.

We have thus found evidence in these two quarries at Llanfawr of three small oval plugs of dolerite which entered the main dolerite mass from below at right angles to its base. Their size in relation to that of the main mass is comparable with that of the stalk which is diagrammatically represented at the base of Gilbert's ideal laccolith. We have thus established that certain intrusions reproduce closely the form as

well as some of the other characteristics of the ideal laccolith, though on a much smaller scale, and that these were fed from below through narrow channels or stalks.

Within the intrusive area at Llandrindod there are numerous small oval outcrops of dolerite which compare in size and shape with the plugs exposed in the Llanfawr quarries; others are almost circular (fig. 3). It is difficult to believe that such small masses could have been concordant intrusions and it is much more probable that most, if not all, of them were feeders to ovoid bodies at a higher level which have been removed by erosion. There are, in addition, some larger masses of oval or elongated form which are discordant in direction with other masses nearby and may also be feeders. They should probably be regarded as short dykes comparable with dolerite masses to be described later in connection with the Welfield complex. The total number of bodies which we infer to be feeders of one type or another is about one-third of the whole or over 100. It is thus probable that there formerly existed in the area at least 100 more concordant masses which have been removed by erosion, but by far the largest number of possible feeders are likely to be concealed beneath the surface.

The concordant ovoid bodies vary in length from about 600 feet to as little as 50 feet; their breadth is usually about two-thirds to three-quarters of their length and in a cross-section the height of the mass is therefore less than half the diameter. These masses tend to be arranged at successive stratigraphical levels through a vertical range of at least 800 feet of shales; this can be seen from the map although it is not immediately obvious. The complex has thus a distinctly layered structure; it is somewhat affected by small folds which cross it nearly at right angles to the general strike of the rocks in this part of the inlier and by two faults which break its continuity.

The former height of the structure is not known. If we consider the space or volume of ground within which the dolerites of the complex have been intruded, it is not unlike an asymmetrical laccolith in form. The base is not everywhere at the same horizon, but examples of laccoliths have also been described in which the base is transgressive.

It is because of the general resemblance between the space

within which dolerites occur and the form of a laccolith that we assign this complex to the laccolith series. The essential feature which distinguishes it from the ideal form is that it is a layered structure composed of shales and discontinuous dolerite masses. We estimate that, as exposed in section at the present surface of the ground, the aggregate area of the outcrops of dolerite is only about 25 per cent of the total area defined by an envelope line drawn around the complex. It is, therefore, a very open structure. Moreover, not more than 25 per cent of the height of the domed form of the envelope can be attributed to the lifting of the strata by the intrusions; the other 75 per cent is to be accounted for by the fact that the layers of intrusions are emplaced at successively higher stratigraphical levels in the shales.

It is clear that the distribution of the ovoid masses, as well as the limits of the structure as a whole, were determined by the distribution of feeders. The height to which igneous material ascended in the shales depended possibly upon the size of the feeders and upon other factors, such as the viscosity of the magma and its temperature. At the time of the intrusive activity the shales probably contained a high percentage of water and we believe that most of the characteristic features of the Llandrindod laccolith are due to the fact that the magma was intruded into these wet shales probably beneath a relatively small thickness of cover (Jones and Pugh, 1948,b).

WELFIELD COMPLEX

We had mapped and described the Welfield complex (1946) before we examined the Llandrindod laccolith. The complex forms a prominent ridge north of the River Wye in which dolerites associated with highly baked shales are well exposed. On the west side, Silurian (Upper Llandovery) rocks rest unconformably on Ordovician dolerites and shales which belong to the *Nemagraptus gracilis* zone. These shales are estimated to be about 1,000 feet (or about 1,200 feet if the dolerites are included) higher in the stratigraphical succession than the rocks exposed in Welfield ridge, which are in the upper part of the *Glyptograptus teretiusculus* zone.

In Welfield ridge 44 separate masses of dolerite have been mapped but as the complex is truncated by a tear-fault on

the north it seems probable that only about one-half of it is seen (fig. 4); the outcrops of most of the masses are oval. At least five of them, however, are different in form from any masses seen at Llandrindod; they are wing-like prolongations from two roughly oval dolerite outcrops which occur near

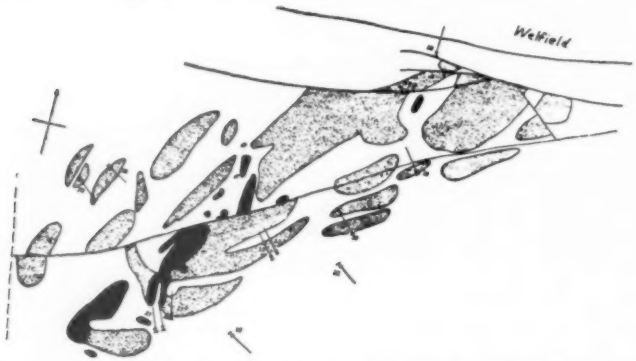

Fig. 4. Map of Welfield laccolith showing feeders and possible feeders in black (other dolerites stippled).

the crest of the structure and are aligned approximately in the direction of its trend. The aggregate area of dolerite outcrops is roughly 50 per cent of the area included between an envelope drawn through the ends of the dolerites and the tear-fault which crosses the complex. From the limited information available the Welfield structure thus has a higher proportion of dolerites within it than the Llandrindod complex. This is in accordance with a rule generally applicable to the dolerites at different horizons within the inlier, which is, that those at lower levels in the stratigraphical succession are more massive and more continuous than those at higher levels.

The Welfield area has been affected by post-Silurian tilting and faulting. If allowance is made for post-Silurian tilting, the Welfield structure had the form of a laccolith with a dip in the western flank of 30° and in the eastern flank of 60°. At the present time the eastern flank dips at about 30° but, a short distance away from the strong feature which defines the eastern margin of the ridge, the Ordovician shales now dip in a westerly direction of 32° to 35°. These westerly dips when corrected for a post-Silurian westerly tilt of 30° become 2° to 5° and in combination with the dip of 60° in

the eastern flank of the structure indicate a sharply defined flexure at the edge of the structure. They imply also that the Ordovician rocks at the time of the intrusive episode were almost horizontal. The corresponding differences in the dips on the western margin are probably only about 10° to 20° and the flexure is not so sharply defined. The existence of these flexures is regarded as an important confirmation of our view that the Welfield complex should be assigned to the laccolithic series.

We have no direct knowledge of the inner core of this laccolith. Since the present surface is a random section through the outer skin of the structure, it is probably fair to assume that the arrangement of dolerite and shale there seen is broadly similar to that which occurs below the surface. In other words, the shales at a deeper level probably include many ovoid intrusions with possibly some wing-like bodies given off from the downward prolongation of the dyke-feeders near the crest of the structure or from similar feeders which do not obviously play this role at the surface. In comparison with the Llandrindod complex it is not unlikely that several other masses which we mapped at Welfield may have been feeders also but at that time we had no reason to assume the existence of any type of feeder other than the two dyke-like bodies to which we called attention. These are shown in black in figure 4. We suggested that the unusual degree of baking of the shales may be due to larger bodies concealed beneath the surface.

COMPARISON OF LLANDRINDOD AND WELFIELD COMPLEXES AND OTHER INTRUSIVE FORMS

It is hardly necessary to recall the similarity between the Welfield complex and the Llandrindod complex. They are both layered structures and they differ only in two respects. The Llandrindod structure lacks the wing-like extensions found at Welfield and the latter contains more dolerites in proportion to associated shales.

In comparing the affinities of the Welfield complex with other intrusive forms we found that its nearest analogues were among the various types of laccoliths which have been described and figured from the Western Territories of the United States of America. We were impressed by the fact that

Welfield ridge or as much of it as can be observed revealed all the features that were considered to be characteristic of laccolithic intrusions. Moreover, the relation of the two short dolerite outcrops near the crest of the structure to the five wing-like masses which spring from them inevitably recalled certain parts of a cedar-tree laccolith.

The Welfield complex is a layered intrusion which stands in an intermediate position between the Llandrindod complex on the one hand and a cedar-tree laccolith on the other; and on this ground we assign both complexes to the laccolith series. They are both determined essentially by the incidence of feeders of one type or another.

It is hardly necessary to point out that the cedar-tree laccolith is one of the most striking examples of a layered intrusion that has yet been described. As represented by Holmes (1877), the individual layers all appear to be lateral or wing-like offshoots from a central mass which acts as their parent feeder; in comparison with the length of the wing-like extensions the central feeder is of considerable size.

Whitman Cross (1984, p. 209) has remarked that "as drawn, this intrusion implies a considerable absorption or assimilation of strata, for which no evidence is given and which is entirely improbable." It would be of great interest if this particular feature in the structure of the La Plata Mountains were re-examined and mapped in detail. In the light of our experience it may be found that the bodies which fed the leaves of the intrusion were less massive and more numerous than is indicated in the sketch by Holmes and that the appearance of incorporation of sediments suggested in that illustration may not be confirmed.

It is easy to envisage other intrusions of broadly laccolithic form in which the proportion of sedimentary rock to intrusive rock is considerably less than in any of the examples already mentioned. The el Late laccolith figured and described by Holmes (1877) and discussed by Whitman Cross (1894) appears to be a good instance. It is worth noting that Holmes was examining this and neighbouring areas at the same time as Gilbert was exploring the Henry Mountains. It is not improbable that the broad concept of the laccolith was already in the air at that time although it did not receive its name until 1877. It may be mentioned also that Holmes' sketches and

in particular the figures of the el Late structure show that he had correctly envisaged the relation of the arching of the strata to the thickness of the underlying intrusion. This is clearly seen in fig. 5, which reproduces Holmes' sections of el Late; the first of these is well-known but the other two may be less familiar.

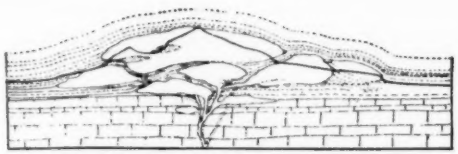

Fig. 1
Section showing probable method of intrusion of masses of trachyte.

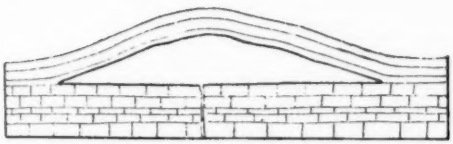

Fig. 2.
Arching of strata produced by intrusion of single mass uniformly distributed.

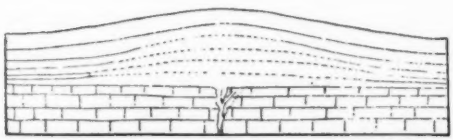

Fig. 3.
Degree of arching really produced by the irregular intrusions.

Intrusion of masses of Trachyte.
Sierra el Late.

Fig. 5. Sections of Sierra el Late by W. H. Holmes (1877).

In the el Late structure the intrusive bodies are separated by relatively narrow partitions of stratified rocks which, so far as can be judged from illustrations, occupy only about 25 per cent as compared with 75 per cent in the Llandrindod complex. No one has any difficulty in accepting the el Late structure as a variant of the ideal form and in regarding it as a compound laccolith. In the el Late laccolith about 75 per cent of the total amount of arching was directly due to the intrusive rock and only 25 per cent to its layered structure as is illustrated in Holmes's figures but it is clear that the

masses in the upper part of the complex were intruded into a higher level of the stratified series than those near the base of the laccolith.

It is unnecessary to discuss the many other types of laccoliths which have been described and are transitional between the el Late laccolith and Gilbert's ideal form in which the whole of the arching of the covering strata is due to the intrusion. If, however, the examples mentioned above are considered together it is possible to recognize every transition between, on the one hand, a much divided structure such as the Llandrindod complex and, on the other hand, Gilbert's ideal form. This is the reason why we assign the rather remarkable intrusive forms displayed at Welfield and Llandrindod to a laccolithic series. Their underlying unity is the form of the space in which the intrusive rock is included and this as in the ideal laccolith is determined broadly by the incidence of feeders. The detailed arrangement of the individual masses which make up the whole structure depends upon many factors. But as Harker (1909, p. 70) says, "In the case of the ideal laccolite intruded in connection with crustal stresses purely of the plateau-building kind, the precise location of the intrusions will depend upon intratelluric conditions beyond our cognisance." So far as the Welsh examples are concerned, we have discussed some of these questions in the publications already mentioned.

COMMENTS ON A NEW INTERPRETATION OF THE HENRY MOUNTAINS LACCOLITHS

Charles B. Hunt (1942) recently claimed that the large symmetrical domes of the Henry Mountains are not due to mushroom laccoliths but have resulted from the injection of stocks. This claim rests not upon actual proof of the internal structure of these mountains but upon certain theoretical considerations. According to Gilbert, these mountain domes resulted from the intrusion of a magma at a certain horizon which lifted up the strata above that level into a dome the height of which depended upon the thickness of the intrusive mass. It was to the igneous rock of this general form that the name laccolith was originally applied; with it were associated sheets of sill-like form, and dykes.

Hunt disguises the issue by re-classifying the igneous rocks

into "stocks, laccoliths, bysmaliths, dikes and sills" (p. 197) but the bodies termed laccoliths are defined as "elongate, tongue-shaped masses that were injected radially into the strata adjoining the stocks" (p. 197). These would appear to correspond in general to Gilbert's sheets and are unessential accompaniments of the main body of the laccolith; their presence or absence has no bearing upon the form of that body. By this somewhat arbitrary re-definition of the term laccolith which seems to rest upon no solid basis, Hunt is able to call by the name of stock what everyone has hitherto accepted as *the* laccolith.

In the very small-scale cross-sections (fig. 1, p. 200) which illustrate the paper there is no indication of the horizontal layers which occur at a lower level than the base of Gilbert's laccolith. These horizontally disposed layers are prominently displayed in several of Holmes' sketches but they have no place in Hunt's theory of these domes. He states that "the stocks of each of the five mountain masses must have been emplaced by physical injection because the space occupied by the stocks would be closed if the formations turned up around the stocks were restored to their original horizontal position" (p. 198). This appears to state no more than that the intrusion made room for itself by pushing away the surrounding strata and applies just as well to the ideal laccolith as to the supposed stocks.

The main argument seems to rest, however, upon the statement that the width of the stock, that is, the exposed part of the igneous mass near the centre of the dome in each of the four mountains, Mt. Holmes, Mt. Ellsworth, Mt. Pennell and Mt. Hillers, "is almost a direct function of the amount of uplift" (p. 198). These are compared with the Navajo Mountains on the Colorado Plateau about 50 miles to the south, which is of about the same diameter at the base (6 miles) as each of the above domes. The Navajo dome uplift is estimated to have been about 2,600 feet; it is calculated that the rocks within the basal perimeter which had an area before uplift of 9π or 28.27 square miles must have occupied after uplift an area on the surface of the dome of 28.75 square miles, indicating an areal increase of 0.48 square mile or 1.7 per cent. It is not clear how this figure was obtained. If the uplift was approximately in the form of a spherical cap, the

increase of area where the height is one-sixth of the radius of the base, as in this case, should be 2.78 per cent or nearly 0.8 square mile. Hunt's diagram (fig. 1) represents the uplift as conical in form, but if this form is assumed the increase in area with the above ratio is about 1.4 per cent or about 0.4 square mile. Perhaps he has adopted some compromise between these extreme forms between which would lie most dome-like uplifts. It is not, however, with the precise amount of the areal increase that we find difficulty but in the argument on which it is based and on the use which is made of it.

In the Navajo dome, according to the author, the stretching by uplift has not been so great that the strata at the summit of the dome have parted so as to allow of igneous intrusion. The increase in area of half a square mile is thus assumed to give a limit to the amount of stretching that can occur in the cover-rocks without rupture, but the validity of this argument is very doubtful. If, for example, the dome were composed of a rock with a modulus of elasticity of about 5×10^6 lbs. per square inch, such a rock would rupture under a linear strain of about 1/2500 inch per inch. This is not very different from what might be caused by simple thermal expansion. The areal stretching just prior to rupture would be 1/1250, which is only about one twentieth of that attributed to the formation of the Navajo dome. It is obvious, therefore, that the increase in area of the rocks of Navajo dome could not be due to simple stretching but must have been accomplished by rupture, probably by the opening of joints. This process once started can go on to an unlimited extent all over the domed surface but possibly more near the crest than down the flanks and, therefore, can give no basis for the assumption that the rocks can stand so much stretching but no more without opening up.

It is then argued that "greater uplift in areas of the same size in the Henry Mountains has resulted in the parting of the strata and the creation of space to accommodate the stocks" (p. 199). In each diagram of fig. 1 (p. 200), the stippled hypothetical area available for the intrusion of each stock has been reduced by an area equivalent to that represented by the stretching of the strata as determined at Navajo dome. Once the basis of the stretching hypothesis has been proved to be wrong it does not follow that the intrusion of a

cylindrical plug-like form is necessary in order that the above relation shall hold. They can be accounted for equally well by assuming Gilbert's ideal laccolithic form, for it is the mere shape and size of the dome that determines these relations and not what is inside it.

There are three features of the Henry Mountains laccolith that tell strongly against this author's interpretation, namely, (1) the existence of horizontal strata below the general level of the inferred base of the laccolith, (2) the distance away from the igneous core to which alteration of the strata has been observed in some cases and (3) the relation of the cover to the igneous core, for example, in Mount Hillers and in Ragged Mountain described by Whitman Cross (1894, p. 181, fig. 29).

We may also add that in our view the injection of a cylindrical plug-like stock must take place by a process of shearing analogous to the driving of a punch into metal; this is accomplished by pushing away and compressing the adjacent material and the effects diminish rapidly as the distance from the shear zone increases. It is therefore most unlikely to give rise to a broad, uniformly curved doming of the strata such as occurs in the Henry Mountains.

According to Hunt, the strata around the Mount Holmes igneous core are metamorphosed and shattered for as much as a mile from the walls of the intrusion. In our experience, this indicates a high probability that the igneous rock is at no great distance below the surface for at least that distance from the exposed margin of the intrusion. In Mount Ellsworth, a narrow tongue-like belt of altered rocks about a mile and a quarter long is represented which likewise suggests the prolongation of the upper surface of the intrusion to at least that distance.

Finally, Hunt appears to agree with some of the arguments presented above, for he remarks that "although the evidence shows that the stocks in the Henry Mountains were forcibly injected, the large domes around the stocks are not necessarily the result of that injection" (pp. 199-200). After considering four hypotheses to account for them and rejecting two which obviously do not apply, he concludes that they may be due either to arching by one huge, deeply buried laccolith of mushroom form or to a vertical push as if by the stocks. He objects

to the first of these hypotheses on the ground that it would necessitate the assumption of an almost perfect symmetrical mushroom laccolith (*the* laccolith of Gilbert), whereas the known laccoliths (of Hunt or sheets of Gilbert) are tongue-shaped, elongate bulges. He remarks, moreover, that the assumed mushroom laccolith would have to be 20 times larger than the largest known laccolith (of Hunt, not Gilbert) in the Henry Mountains and about 50 times larger than the average volume of all known laccoliths (again of Hunt) in these mountains. Here we have examples of the confusing effects of the author's attempt at restricting the name laccolith to certain forms arbitrarily selected by himself.

He considers also that the growth of a laccolith to such huge size would probably result in imperfect form. We would comment that in the absence of directional stress a symmetrical form is the most likely to be produced.

A paragraph near the end seems to explain why the above suggestions are made by the author, "Although it is perfectly true that the domes could be the result of arching over laccoliths (? of Gilbert), they could as readily be the result of doming by stocks like those (assumed to occur) in the Henry Mountains. The object of this paper is to stress the need for reconsidering the explanations hitherto applied to large symmetrical domes associated with igneous intrusives." (p. 203.) The words in parentheses in this quotation have been inserted by us.

Our experience in Wales leads us to believe the truth of Gilbert's magnificent conception and we have also been fortunate enough to discover the stalks through which masses of laccolithic form, though on a very small scale, were fed.

Finally, Hunt refers to explorations by boring in the laccolith of the Marysville Buttes described by Howell Williams (1929). Although the original intrusion of the Marysville Buttes is regarded by Howel Williams as a steep-domed laccolith it has been considerably affected by subsequent volcanic and intrusive activity so that its original form has been almost destroyed. It is perhaps significant that a volcanic vent was later opened up just where one would assume the stalk of the original laccolith to have been. Is this accidental or may it give a hint of the existence of a stalk situated centrally below the original laccolith?

Hunt mentions several borings which were carried down for several thousand feet on the flanks of the structure; one of these was within a few hundred feet of the exposed outcrop of the igneous core and was carried to a depth of 7,014 feet. This did not reveal a continuous mass of igneous rock but a number of sills intruded into the domed strata. If a similar boring were put down, say, into the core of the Welfield laccolith, we should expect, in view of our present knowledge of these structures, to find numerous thin intrusive sheets interleaved with sediments and it may be that a similar state of affairs may occur in connection with laccolithic bodies more frequently than has been supposed.

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METASOMATIC GRANITIZATION OF BATHOLITHIC DIMENSIONS

PART II. STATIC GRANITIZATION IN SHEKU AREA, NORTHWEST YUNNAN (CHINA)[1]

PETER MISCH

ABSTRACT. Near Sheku in Northwest Yunnan, red beds deposited after late Triassic orogeny and barely affected by later Mesozoic orogeny which is important in neighboring parts, have been statically granitized within an area measuring 13 by 20 miles as mapped. The rocks can be described as "granodiorite-porphyries." They occur in irregular bodies formed entirely by metasomatic transformation of sediments. The virtually flat-lying red beds enclosing the granodioritic bodies, as well as relict inclusions of red beds in these bodies, have not been displaced. Some of the stratification of the red beds seems to have been preserved in the granitized rocks. The groundmass of the "granodiorite-porphyries" has the clastic texture and composition of the fine-grained quartzose-argillaceous red beds bordering the igneous-appearing rocks. Apparent phenocrysts of calcic oligoclase, microperthite, quartz, and subordinate hornblende and biotite are porphyroblasts showing replacement features. There are all stages from early crystalloblastic growth to "euhedral" porphyroblasts imitating phenocrysts. Apparent resorption embayments in quartz have formed by differential crystalloblastic growth.

The essential material added was alkali, with sodium predominating. The amount was small. Introduction was by rising solutions which also conveyed heat. Metasomatism occurred at an unusually shallow depth, and at a moderately high temperature. Recrystallization of the red beds near the granitized bodies was incomplete, restricted, and predominantly at low temperature. In contrast to most areas of static granitization, there was no regional heating and recrystallization of the sediments outside the granitized bodies. This feature, the general preservation of clastic relict texture in the transformed rocks, and their porphyritic-appearing texture are attributed chiefly to the shallow depth. The Sheku type of static granitization is compared with the "normal" type which in large transformed bodies produces "eugranitic"-appearing textures. Amount of introduced material, and removal of some of the original material versus increase of volume, are discussed.

INTRODUCTION

THE general problem treated in the present paper has been stated in the introduction to the first part published in the April issue of this JOURNAL. In the first part, it has been shown that synorogenic granitization is capable of producing vast areas of gneiss-granitic rocks. The intimate relations between orogenic regional metamorphism and synkinematic granitization have been discussed and certain general conclusions suggested. After orogeny in geosynclines batholithic masses of

[1] Read during Geological Society of America, Cordilleran Section, 1948 meeting at Pasadena.

granitic rocks are widely formed under static conditions. Do they owe their origin to magmatic intrusion or to metasomatic transformation of pre-existing rocks or to both? Among examples which I have had an opportunity to study in the field, an area is here described in which unusually favorable conditions permit of establishing a metasomatic origin of entire granitic masses, and not only their marginal portions. Then, this case is compared with other types of static granitization. For a recent review of the history of the ideas involved in granitization, I again refer to the 1948 Granite Memoir of the Geological Society of America, especially to H. H. Read's contribution.

I. OUTLINE OF GEOLOGY OF SHEKU AREA, NORTHWEST YUNNAN[2]

The area described is in the geosyncline which I found to occupy Western Yunnan, near the southwestern border of China (Misch, 1945 b). The area is west and south of Sheku, a town located on the bank of the upper Yangtsekiang where this river abruptly changes its southern course and turns back in a tremendous sweep. A geologic reconnaissance map of the area is given in plate 9, and a general section along the main traverse studied, in figure 1.

In this area there are three main groups of rocks: (1) *intensely folded and in part dynamically metamorphosed sediments and volcanic rocks ranging in age from pre-Cambrian(?) to Triassic*, (2) *a thick series of unconformable Mesozoic red beds*, and (3) *granitic rocks later than the red beds*. The sequence of formations composing the first group is outlined in the legend of the map (pl. 9). The granitic rocks treated in the present paper come on the east partly in contact with the oldest formation in this area, the presumably later pre-Cambrian *Sheku schist* (cf. Misch, 1945b, p. 51-52). It consists of thick micaschists grading into phyllites and is "upper"-mesozonal and "low"-epizonal. This formation, and *Paleozoic and Triassic rocks* which in most parts are epizonally meta-

[2] My field work in northwest Yunnan extended from 1939 to 1946, under the auspices of the National University of Peking which during that period was incorporated in the National Southwest Associated University at Kunming, Yunnan, and of Chinese Government institutions. The field work in the Sheku area was carried out in 1940 and 1945. I wish to thank Prof. Y. C. Sun, Director of the Geology Department at the National University of Peking, for his permission to use for this paper the material collected in the field. Most of the petrographic work was done in the Geology Department at the University of Washington.

morphosed, are involved in strong folding and complex thrusting which includes movement of older over younger as well as of younger over older rocks (cf. Misch, 1945a, p. 541-543). The latest fossiliferous rocks involved in this orogeny are of *early Norian* age (*Paratibetites adolphi*, etc., cf. Misch, 1947, p. 109-110). The western part of the area (cf. pl. 9) is composed of Triassic red beds and marine sediments associated with thick porphyries and rhyolites. These rocks are steeply folded. *Cardita crenata* indicates that Carnian is represented.

All these rocks are with strong angular unconformity overlaid by a thick succession of continental red beds, including shales, fine-grained sandstones, grits and conglomerates. This formation belongs to the writer's "upper red beds" of Yunnan (Misch, 1945b, pp. 98-102 and 145-148, and Misch, 1947, pp. 106-109).[3] In several areas the "upper red beds" are conformable with partly fossiliferous (lower) Norian black shales and gray sandstones. There the "upper red beds" include Rhetian, if not upper Norian, though they presumably extend far into the Jurassic. In the region here described, *intense Late Triassic orogeny* has taken place before the deposition of the "upper red beds"(cf. Misch, 1945b, p. 148), and it is therefore uncertain whether they also here began to form during the latest Triassic, or whether deposition did not begin till Jurassic time. A Jurassic age of the main part of the "upper red beds" seems to be confirmed by the discovery, in the southern part of the area shown in plate 9, of an intercalated limestone member in which a few supposedly Jurassic marine fossils were found. The thickness of the "upper red beds" west of Sheku is over 10,000 feet, to which has to be added an unknown thickness removed by erosion.

Late Triassic orogeny was intense in the area here described, but was found to be lacking in wide parts of the West Yunnan geosyncline. In most parts of the geosyncline, it was succeeded by equally intense *later Mesozoic orogeny* (cf. Misch, 1945a, and 1945b, pp. 119 and 122-123). "Upper red beds" were also involved in epizonal dynamometamorphism and overthrusting. However, in the area here described, this second orogeny is almost lacking. Most of the "upper red beds" are practically

[3] I have classified the Mesozoic red beds of Yunnan into "lower red beds" = Lower Triassic; "middle red beds" = Middle and lower Upper Triassic; and "upper red beds" = highest Triassic and, in large part, presumably Jurassic. The first two divisions I have shown to interfinger laterally with marine sediments.

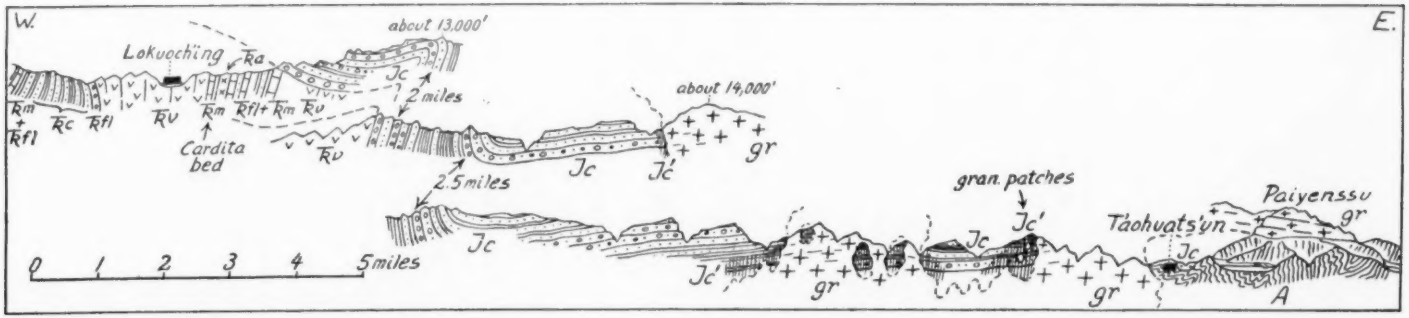


Figure 1. Section west and southwest of Sheku, Northwest Yunnan. Location of sections is marked on the map (pl. 9)

gr : "granodiorite-porphyry"
Jc : "upper red beds," Jurassic (and highest Triassic?)
Jc' : the same, more or less recrystallized
Tr v : rhyolites and porphyries, presumably Triassic
Tr a : Triassic andesite
Tr m : marine Triassic limestones and shales, including Carnian with *Cardita crenata*
Tr fl : Triassic flysch, gray sandstones with shales and conglomerates, partly continental
Tr c : "middle red beds," Middle and lower Upper Triassic
A : Algonkian micaschists

PLATE 9. *Geological Reconnaissance Map of Part of Northwest Yunnan (China)*

Q : Quaternary (smaller areas omitted)
Pc : Pliocene, lake beds and some gravels
Ta : Tertiary biotite-andesite
KTv : dacitic and andesitic flows, Cretaceous or Tertiary
gr : metasomatic "granodiorite-porphyry," Jurassic or Cretaceous; with local diorite
grp : pegmatite connected with gr
Jfe : felsite and related rocks, (?)Jurassic; probably transformed Jc
Jc : "upper red beds," Jurassic (and Rhetian ?)
Jc'' : the same, more or less incompletely recrystallized
JTr c : "middle" and/or "upper red beds"
JTr' c : the same, epizonally metamorphosed (phyllites, etc.)
Tr cp : calc-phyllite, Upper Triassic; with quartz-dioritic dikes made into mylonite-schists
Tr_3 : Norian black shales and gray sandstones (marine with continental intercalations)
Tr'_3 : the same, epizonally metamorphosed (black phyllites, etc.)
Tr_2 : Ladinian and Carnian massive limestone (continuous in eastern facies; forming lenses and bands in western facies)
Tr fl : flysch; black shales and gray sandstones, continental and marine; probably including some Tr_3 } lateral equivalents of Ladinian-Carnian limestone in western facies
Tr c : "middle red beds" } lateral equivalents of Ladinian-Carnian limestone in western facies
(Tr ?)ls' : foliated limestone with some calc-phyllite; equivalent to Tr_2?
Tr a : Triassic andesite
qd : quartz-diorite-porphyry, Triassic or later
Tr v : rhyolite and porphyry, presumably Triassic
Tr v' : the same, epizonally metamorphosed (schistose porphyroid)
Tr_1 : { Anisian shaly limestone } lower Middle and { Scythian red beds ("lower red beds") } Lower Triassic
uPm : Upper Permian marine shale
Pm v : Permian basalt (with intermediate and ultrabasic flows)
Pm v' : the same, epizonally metamorphosed (greenschists, etc.)
Pm ls : Lower Permian massive limestone
Pals : Devonian-Carboniferous massive limestone (possibly including some Lower Permian)
Pam : the same, epizonally metamorphosed (banded marble, etc.)
O : Ordovician shale, phyllite, and quartzite
A : Algonkian(?) micaschist
Ar : Archaean gneiss
S—S' : sections in text fig. 1.

undisturbed. Only in the western portion of the area are they folded (cf. fig. 1), but their folding is much weaker than that of the older rocks. In the area described, the "upper red beds" do not show any trace of differential deformation or dynamic metamorphism.

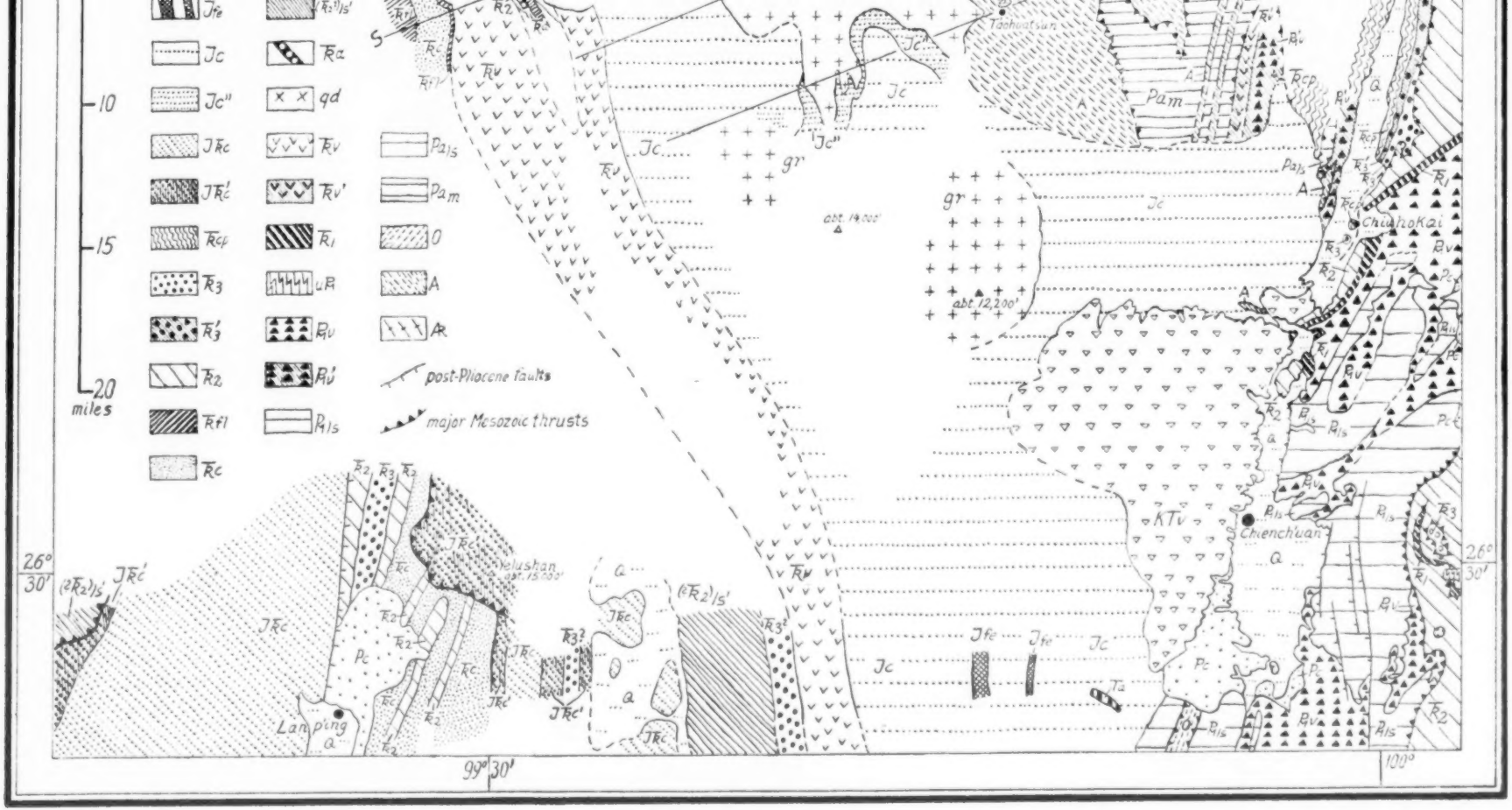
Within an area measuring about 13 by 20 miles as mapped, the "upper red beds" contain *irregular bodies of massive granitic rocks.*[4] They show a definite tendency to keep to the red beds, and only in the east do they partially come in contact with the underlying Sheku schist. Since the granitic-appearing rocks are later than the "upper red beds," they are considerably younger than the Late Triassic main orogeny in this region. Whether they are also later than the second, e.g. post-"upper red beds," orogeny of West Yunnan is uncertain since in the region here described this orogeny has acted only weakly and locally, and has not affected the "upper red beds" where they enclose granitic masses (not, at least, at any localities I have visited). The granitic rocks were formed under static conditions and completely lack structures indicative of stress, either inherited, contemporaneous or superposed. The age of the granitic rocks is presumably Late Mesozoic. Exact stratigraphic dating is impossible since there are no definite Cretaceous rocks known in West Yunnan. Not far east of the region here described, thick conglomerates and breccias are widespread which are younger than all the rocks so far described. I have tentatively assigned an Early Tertiary age to these conglomerates (cf. Misch, 1945b, pp. 133 and 152). In the southeastern part of the area shown in plate 9, the "upper red beds" are unconformably overlaid by flat-lying andesitic and dacitic flows and tuffs which are possibly Cretaceous but more probably Tertiary.

II. FIELD EVIDENCE OF METASOMATIC GRANITIZATION[5]

How have the granitic masses acquired their position within the red beds? Traditionally, they would be termed intrusive,

[4] The term "granitic" is here used purely descriptively and in its widest sense (including granitic *s. str.* and granodioritic, evengranular and porphyritic rocks), and chiefly based on appearance in the field.

[5] The term "granitization" is here used in a wide sense, as defined by F. F. Grout (1941, p. 1540) according to whom it "*includes a group of processes by which a solid rock is made more like granite than it was before, in minerals, or in texture and structure, or in both.*" The products of granitization are therefore not always granites, though granite is the final goal.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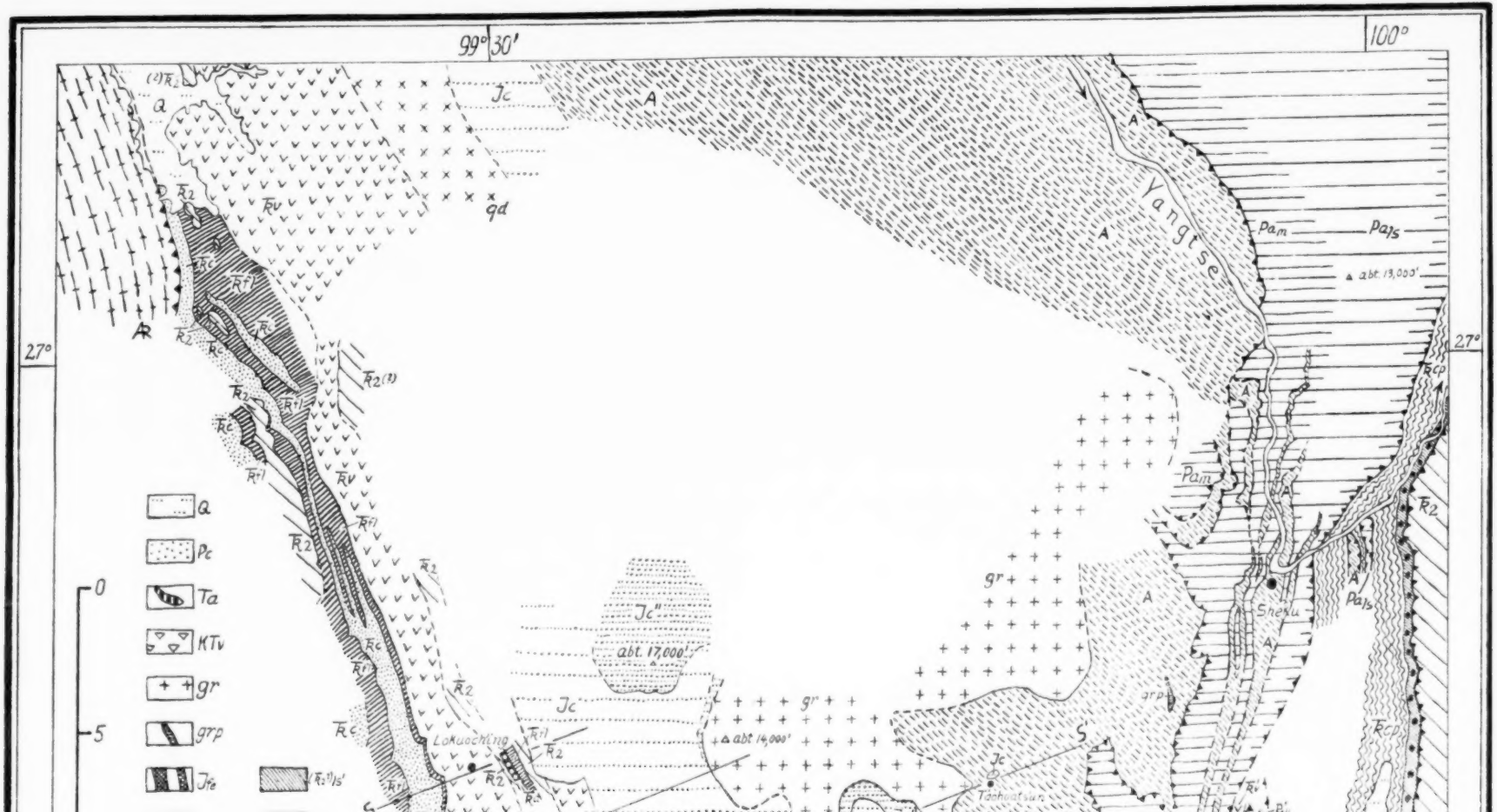
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and the question considered answered, but *field relations do not show any indication of mechanical emplacement by magmatic intrusion.* As in many postorogenic granitic masses, the picture is one of the granitic rocks filling an irregularly shaped space formerly occupied by sediments, without these sediments being visible anywhere—as if someone had with a pair of scissors cut out certain parts of the sedimentary section in a haphazard manner and substituted granitic rocks. In the region here described, this situation is particularly striking, because *the red beds enclosing the granitic masses are undisturbed,* whereas in other areas the enclosing sediments have usually been folded prior to formation of the granitic masses.

The field relations in the Sheku region, as observed along the main traverse surveyed, are shown in figure 1. The almost horizontal position of the red beds excludes the possibility of mechanical emplacement of magma by doming. Locally an extremely gentle dip of the red beds away from the contacts was noticed. It cannot possibly be an indication of doming by intrusion, since it would take tilting many times stronger and much more widespread, to create the room needed to accommodate even the visible granitic masses. If those extremely slight and local dips are at all related to the granitic masses, they would indicate an upward movement infinitely small compared to the volume of the granitic masses. A very slight increase of volume during metasomatic transformation of sandy argillaceous sediments into granitic rocks could account for this (cf. chapter IV).

There are smaller and larger *bodies of red beds enclosed in the granitic masses.* Their bedding has remained practically horizontal, as in the red bed areas adjacent to the granitic outcrops. This complete lack of disturbance and disruption of the stratification of the sediments is remarkable. It is contrary to magmatic intrusion which would of necessity imply mechanical displacement of the sediments, irrespective of what mechanism of intrusion is suggested. The absence of doming has already been discussed. Nor can stoping have been the means of emplacement. For in this case, red bed bodies enclosed in the granitic masses would show evidence of sinking, which is not the case, and at least most of them would have lost their horizontal position. Generally speaking, it is difficult to conceive

how fragments of wall rock could be enclosed in magma without being rotated and shifted. Nor is there any indication of an upward movement of the red bed bodies enclosed in the granitic rocks.

I conclude that no intrusive mechanism could account for the field relations observed. How then can the "mysterious disappearance" of the sediments from the space now occupied by granitic rocks be explained? The only possible answer appears to be that *the sediments have not disappeared at all.* They are still there, but *have by metasomatic processes been transformed into granitic-appearing rocks.* No great chemical change was needed to achieve this result. The sandy and silty shales and fine-grained argillaceous sandstones which predominate in the red beds laterally prolonging the exposed granitic masses, hardly needed more than an addition of some alkali to acquire a granitic composition (essentially sodium, as the igneous-appearing rock is granodioritic; cf. chapter IV).

Those granitic outcrops and specimens I have examined, *lack any trace of flow structure*, either megascopic or microscopic. As will be shown below, these rocks consist of a fine-grained groundmass and larger crystals among which are columnar hornblende and tabular biotite. Such rocks would be rather well suited to record magmatic flow—if they were of igneous origin. On the other hand, at some places there are *suggestions of sedimentary relict bedding* in the igneous-appearing rocks. The precipitous south face of Paiyenssu where the granitic rock is unusually well exposed (cf. fig. 2), shows a structure strongly suggestive of nearly horizontal bedding, and parallel to the stratification of the red beds which prolong the granitic rock on the west (cf. also fig. 1, lower section, east part). The lower slopes of Paiyenssu consist of steeply folded Sheku schists. They underlie the red beds in this vicinity. The south face of Paiyenssu seems to consist of flat-lying granitized red beds. They are topographically above the old schists and presumably overlie them normally.

Where the *contacts* between the granitic-appearing rocks and the red beds were observed, they are usually rather sharp. This might be taken as evidence against granitization, but it appears that replacement is apt to produce both gradational and sharp contacts, depending on whether the replacement

"front" remained stationary after reaching its maximum extent, and also on local controlling discontinuities in the replaced rock, such as slickensided fractures and joints. That granitization is able to produce sharp contacts, was first pointed out by C. E. Wegmann (1935, pp. 326-327), and has since been confirmed by several geologists.

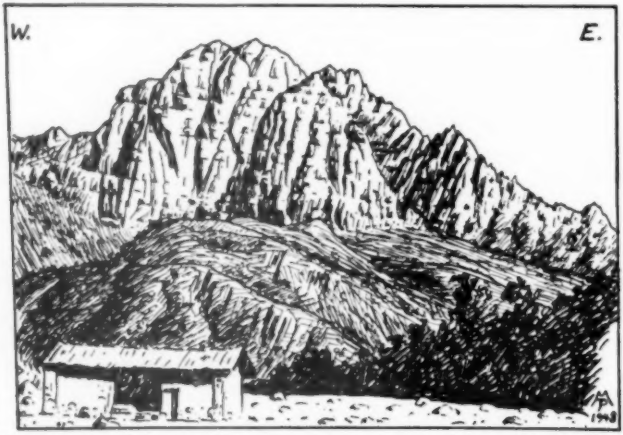


Figure 2. South face of Paiyenssu about three and a quarter miles northeast of T'aohuats'un, southwest of Sheku. Massive "granodiorite-porphyry" showing faint horizontal bedding. The soft lower slopes are composed of Sheku schist.

The interpretation of the granitic-appearing rock as a product of metasomatic transformation is further supported by *some small granitized patches* which were observed in altered red beds outside the larger granitic masses. A good example is exposed on the trail in the valley of T'aohuats'un (cf. fig. 1), and is shown in figure 3. The granitized patches have irregular outlines, and their contacts with the enclosing altered sediments are in part gradational and in part sharp, especially where control by joints is evident. These small granitized patches completely resemble the "small granodioritic blocks formed by additive metamorphism" described by G. E. Goodspeed (1937a) from Cornucopia in Oregon, and have formed in the same manner.

III. PETROGRAPHIC EVIDENCE OF GRANITIZATION

(a) *Description of altered red bed sediments*

Along their contacts with the granitic masses, the red beds have been altered to gray rocks of the appearance of fine-

grained hornfels. The zone of alteration varies greatly in width (cf. fig. 1, and pl. 9). In most places it is narrow and locally

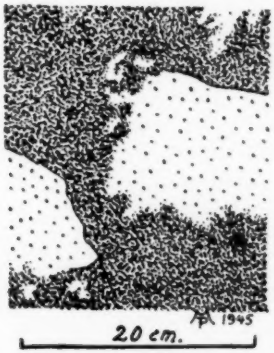


Figure 3. Replacement patches of "granodiorite-porphyry" in recrystallized argillaceous sandstone. About two and a half miles west-southwest of T'aohuats'un, southwest of Sheku.

it is not developed at all. Among localities showing a wide alteration zone, the high peak (about 17,000 feet) in the central part of the map (pl. 9) shows a peculiar section. Its lower south slopes are composed of unaltered red beds, which in its higher parts grade into gray altered rocks. The bedding is conformable from foot to summit, and probably the upper part entirely consists of altered red beds. Whether any granitized rocks are present, or whether they have been all eroded, is not known. More detailed work is needed than could be done during a rapid traverse, under the protection of a bodyguard of tribesmen armed with crossbows, of this bandit-ridden mountain range.

Under the microscope, the altered red beds reveal well-preserved *clastic textures*, and usually show a surprisingly *low degree of recrystallization*. Samples of dense-appearing to very fine-grained gray, brownish and greenish-gray rocks from the *western contact of the granitic mass in the valley of T'aohuats'un* and from *relict inclusions in the western portion of that mass* (traverse shown in fig. 1) show varying amounts of *small clastic quartz grains* set in a turbid matrix (pl. 2, fig. 1). The quartz grains are clear, and their shapes are angular to subrounded. Some of them have, due to beginning crystalloblastic growth, developed small projections and acquired

amoebaelike outlines. The *matrix* is mostly turbid and stained by iron. Its constituents are variable amounts of *carbonate* and of presumably *kaolinitic material*, usually with *epidote*, some ill-defined *alkaline feldspar*, sometimes *sericite* and small amounts of *chlorite*. Epidote is rarely absent and its amount may be considerable. Most of it is present as irregular crystalloblastic patches lacking well-defined borders. Well-formed grains are occasionally found. Sometimes small projections of epidote are seen to penetrate clastic quartz grains. *Magnetite* forms tiny grains scattered in the matrix, or has concentrated in larger grains of irregular shapes. It is derived from the hematitic pigment of the original red beds. Apart from some ill-defined groundmass feldspar, there occur somewhat larger plagioclase grains, partly turbid and partly clear. Some of them may be clastic, and some newly formed. Occasional small flakes of muscovite and of pale brown biotite were observed. All these rocks are derived from fine sandy red shales and argillaceous fine-grained red sandstones, both calcareous, and laterally pass into these unaltered sediments. In a relict inclusion of altered red beds preserved in the granitic mass (fig. 1), a bed with megascopically visible small quartz pebbles occurs.

Samples of altered red beds from the *mountains south of the area just described*, include *similar rock types* (pl. 1, fig.1) and, in addition, *such showing a higher degree of recrystallization* which, however, still remains incomplete. Clastic grains of clear quartz are usually present. They are lacking in a few specimens derived from non-sandy argillites. *Epidote* and *sericite* are often present. Many samples contain amphibole. Pale green *actinolitic amphibole*, sometimes accompanied by a colorless amphibole, forms ill-defined crystalloblastic patches and feltlike aggregates, and rarely better developed larger grains. Dark green *hornblende* may occur in the same rocks, or independently. Its grains are usually better formed, and mostly larger. They occur singly, in patches, and compact aggregates. Sometimes, crystal form is approached. Often, green hornblende is segregated in microscopic veinlets, some of which clearly follow fractures. A few specimens are rich in brown *biotite*, which in one rock is accompanied by a large amount of idioblastic tourmaline. Most specimens contain *magnetite*. One specimen contains turbid sieve-textured *feldspar*

porphyroblasts with crystal outlines. Another sample contains, in a poorly recrystallized extremely fine-grained groundmass, *composite patches of well crystallized hornblende and plagioclase.* Some of these patches have three- and four-sided outlines (pl. 7, fig. 2), and recall, on a microscopic scale, the "granodioritic blocks" described by G. E. Goodspeed (1937a) from Cornucopia, Oregon. Another specimen (pl. 6, fig. 2) has a finely brecciated sedimentary texture, containing angular quartz grains of various sizes some of which show strain shadows, and fragments of fine-grained quartzite or chert partly showing bedding. Some of the quartz has recrystallized as a mosaic free from strain shadows. Between the clastic particles, green hornblende has grown, and has partly concentrated in compact crystalloblastic aggregates. In this rock, all argillaceous matter and all carbonates originally present in the matrix have been used up to form hornblende. All other specimens examined still possess a *poorly recrystallized extremely fine-grained matrix*, locally with a "fluffy" appearance.

The generally rather low degree of crystallization and the mineral facies of the altered red beds described, show that the temperatures to which these rocks were subjected cannot have been very high. The contrast to true hornfels is certainly striking. An additional reason for the surprisingly low degree of crystallization and the small grain size of the newly formed minerals, is the complete absence of differential mechanical deformation in these rocks.

(b) *Description of granitized rocks ("granodiorite-porphyries")*

The granitized rocks are massive and light gray to white. Their *appearance* in the field is *granitic.* They form high massive mountains and rugged faces, such as Paiyenssu ("White Stone Cliff") southwest of Sheku. *Megascopically*, the rock shows a medium-grained fabric of feldspar, quartz, and subordinate hornblende and biotite. Feldspar exceeds quartz. Large phenocryst-like quartz grains are common. They grade from rounded grains resembling small pebbles, to bipyramids. In the "interstitial" spaces, there is a megascopically very inconspicuous groundmass of light color. In a few places, varieties containing little or no quartz and relatively richer in mafics were observed. Although the field relations of these

varieties have not been studied in detail, they are believed to belong together with the more acidic predominant rock type.

Microscopically, the feldspar grains are seen to be predominantly *calcic oligoclase*. Zoning is common, and is mostly recurrent. Frequently there are a dozen or more recurrences, and there may be as many as twenty. The composition of the plagioclase usually varies between An 25 and An 30. Occasionally there are cores of sodic andesine (An 31-32, An 33-34). Sometimes there are narrow rims of more sodic oligoclase (An 23, An 21, An 20). Otherwise, the variation of the anorthite content in individual zoned plagioclases rarely exceeds 4%, and commonly it is much less in adjacent recurrent zones. *Potash-feldspar* is associated with the plagioclase, forming grains of the same size. It commonly encloses plagioclase, is often intergrown with it, but also forms independent grains. Part of it is developed as microperthite. The amount of potash-feldspar is variable, but is usually considerably smaller than that of plagioclase. *Quartz* forms independent grains of various sizes. It frequently shows those embayments which are customarily attributed to "magmatic resorption"; it will be shown in chapter (c) that these are due to growth. The mafics are green *hornblende* and brown *biotite*. They do not attain the size of the feldspar and quartz grains. Hornblende is occasionally absent, but usually exceeds biotite. All these constituents vary from well formed crystals to irregular grains. Their textures will be described in chapter (c). Among accessories, *sphene* is usually present in comparatively large amounts, though occasionally it is lacking. *Apatite and magnetite* are generally present. Sometimes a small amount of *zircon* occurs. Occasionally some tourmaline is found.

All these minerals occur in a fine-grained *groundmass* consisting mostly of quartz and potash-feldspar, with some plagioclase. In most rocks the large crystals considerably exceed the groundmass, and therefore the megascopic appearance of the rocks is granitic or granite-porphyritic. In specimens from widely distant localities, and from marginal as well as interior portions of individual granitic-appearing outcrops, the groundmass consists of clastic-appearing angular and subrounded grains of clear quartz in a matrix of frequently turbid and sometimes iron-stained potash-feldspar (determined by its

PLATE 1

Fig. 1. Incompletely recrystallized fine-grained argillaceous red bed sandstone. Clastic quartz grains, in part beginning to grow. Groundmass green hornblende and quartz. Crossed nicols. South of upper part of T'aohuats'un valley, south of Hsiaoch'iaot'ou (specimen no. 28.12.45.28).

Fig. 2. Metasomatic "granodiorite-porphyry." Crossed nicols. Groundmass of altered fine grained argillaceous red bed sandstone still shows clastic quartz grains. Center: incipient stage of crystalloblastic growth of replacement plagioclase. Below: part of a more advanced plagioclase porphyroblast. Upper right: hornblende porphyroblast. Northwest of Chench'uan (no. 22.1.46.1).

PLATE 2

Fig. 1. Incompletely recrystallized sandy red bed argillite. Clastic quartz grains in turbid matrix with crystalloblastic epidote, carbonate, and some alkali feldspar. Crossed nicols. Upper T'aohuats'un valley east of Hsiaoch'iaot'ou, near western contact of "granodiorite-porphyry" (no. 28.12.45.4).

Fig. 2. Metasomatic "granodiorite-porphyry." Crossed nicols. Groundmass of clastic quartz grains cemented by alkali feldspar. Early stages of porphyroblastic growth of replacement plagioclase. Paiyenssu northeast of T'aohuats'un (no. 29.12.45.3).

PLATE 3

Metasomatic "granodiorite-porphyry." Crossed nicols. Porphyroblastic growth of plagioclase in clastic-derived groundmass. East of Chimaoku (no. 27.12.45.7).

Fig. 1. Large composite plagioclase porphyroblast. Below: quartz crystal.

Fig. 2. Detail of the same plagioclase porphyroblast (area marked by circle in fig. 1), showing replacement border.

PLATE 4

Advanced stages of porphyroblastic growth of replacement plagioclase in metasomatic "granodiorite-porphyhy." Crossed nicols.

Fig. 1. Crystal faces have developed, but relict inclusions of clastic quartz grains of the groundmass are still present. Northwest of Ch'ench'uan (no. 22.1.46.2).

Fig. 2. Final stage: the plagioclase has acquired crystal form and cleared itself of inclusions, imitates a phenocryst. Above: a less advanced plagioclase porphyroblast, still showing replacement borders. West of T'aohuats'un (no. 28.12.45.31).

PLATE 5

Advanced stage of growth of quartz porphyroblast in metasomatic "granodiorite-porphyry." Crossed nicols. West of T'aohuats'un (No. 28,12.45.31).

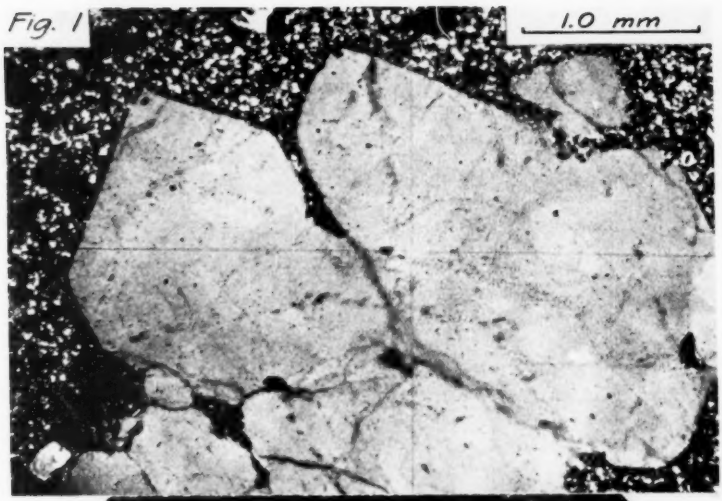
Fig. 1. General view. The quartz grain has the appearance of a phenocryst with "resorption embayments."

Fig. 2. Detail of the same quartz grain (area marked by circle in fig. 1), showing growth surface of porphyroblast invading the groundmass.

PLATE 6

Fig. 1. Early stage of porphyroblastic growth of quartz grain in metasomatic "granodiorite-porphyry." Growth surface as in pl. 5, fig. 2. Crossed nicols. Northwest of Chiench'uan (no. 22.1.46.1).

Fig. 2. Larger clastic quartz grain before crystalloblastic growth. In altered finely breccious argillaceous red bed sandstone. Plain polarized light. Dark areas are newly formed hornblende. South of upper part of T'aohuats'un Valley, south of Hsiaoch'iaot'ou (no. 28.12.45.28).



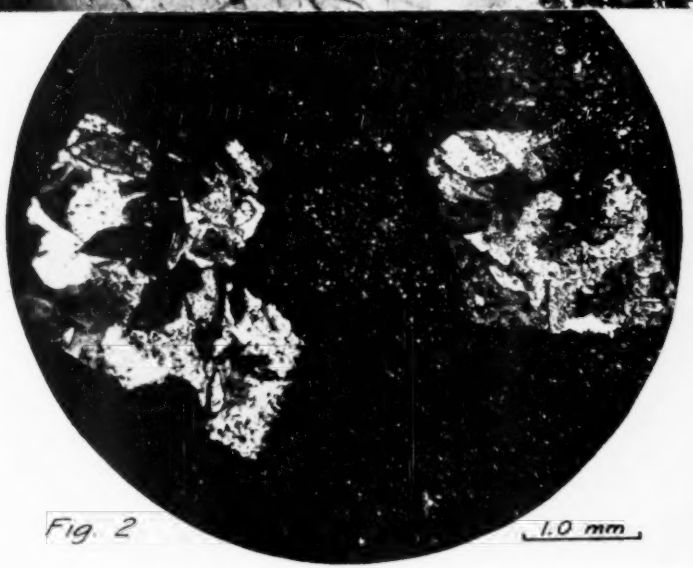


PLATE 7

Fig. 1. Advanced stage of porphyroblastic growth of quartz in metasomatic "granodiorite porphyry." Crossed nicols. Between two idioblastic projections of the quartz grain an embayment of relict groundmass has been spared out, imitating a resorption embayment. Another projection of the same crystal is xenoblastic and encloses groundmass grains. Paiyenssu northeast of T'aohuats'un (no. 29.12.45.4).

Fig. 2. Incompletely recrystallized very fine grained clastic red bed sediment, containing "dioritic" crystalloblastic patches of green hornblende and plagioclase. Crossed nicols. South of upper part of T'aohuats'un Valley, south of Hsiaoch'iaot'ou (no. 28.12.45.15).

PLATE 8

Fig. 1. Porphyroblastic growth of biotite in clastic-derived groundmass of metasomatic "granodiorite-porphyry." Comparatively early stage. Crossed nicols. East of Chimaoku (no. 27.12.45.7).

Fig. 2. Incipient stage of sodium metasomatism of Sheku type in fine-grained clastic Triassic sediment south of Mat'oushan (no. 13.1.46.5). Crossed nicols. Small relict clastic quartz grains, xenoblastic albite, and chlorite.

low index of refraction and its low birefringence; for other methods of optic determination, the grain size is too fine). Some quartz grains of the groundmass develop projections of amoebae-like shapes, in the same kind of matrix. Subordinately fine-grained mosaic of recrystallized quartz occurs. In other specimens, also from widely distant localities, the groundmass consists of a felt-like intergrowth of "fluffy" potash-feldspar (determined as above) and quartz, mostly with varying amounts of plagioclase which occasionally has developed into well formed tiny crystals. There are also transitions between the "clastic type" and the "felty type" of groundmass. They show angular clear quartz grains as well as an intergrowth of irregular amoebae-like small crystals and felty aggregates.

Some further textural features will be described in chapter (c) where the replacement origin of these rocks is discussed. The general appearance of most of these rocks is remarkably uniform in the wide area shown in the map (pl. 9). There is no recognizable mineralogical or textural difference between the marginal and the interior parts of the individual outcrops studied. *In a purely descriptive way*, the rock may be named "*granodiorite-porphyry*."

More basic varieties with little or no quartz were collected locally southwest of Sheku and northwest of this town where they seem to be more common. They contain diopsidic pyroxene which usually shows irregular crystalloblastic growth and pronounced sieve texture though more compact grains occur. Green hornblende of similar texture may replace part of the pyroxene. Subordinate biotite forms small patches in pyroxene and hornblende, and also occurs in irregular grains showing sieve texture. There is much plagioclase, but potash-feldspar may be lacking. The few specimens of this rock do not possess a groundmass comparable to that of the "granodiorite-porphyry" though larger porphyroblasts may be contrasted to an enclosing granoblastic fabric. As stated above, this "dioritic variety" probably belongs together with the more acidic predominant rock type.

(c) *Metasomatic origin of "granodiorite-porphyry"*

A replacement origin of the "granodiorite-porphyry" is suggested by the clastic relict texture of its groundmass and

by the porphyroblastic nature of its apparent phenocrysts.

(1) *Clastic derivation of the groundmass*

As the description of the altered quartzose-argillaceous red bed sediments on the one hand, and of the groundmass of the "granodiorite-porphyry" on the other hand suggests, and as a glance at the photomicrographs in plates 1-8 confirms, both show an extremely strong resemblance. Both contain the same small clastic grains of clear quartz. In both rocks, relative amount, shape and size of these grains vary within the same limits. In both rocks, clastic quartz grains frequently show small projections due to beginning growth. In both rocks, these tiny clastic grains are cemented by a more or less turbid and frequently iron-stained matrix. In the altered red bed sediments, this matrix is very incompletely recrystallized, often still containing kaolinitic-appearing material, and sometimes containing low-temperature new minerals such as sericite and chlorite; it is rich in carbonate, and epidote is the chief new mineral whereas alkali-feldspar is subordinate. In the groundmass of the "granodiorite-porphyry," the cement between the clastic quartz grains has on the whole somewhat cleared itself and has mainly recrystallized as alkali-feldspar; carbonate and epidote, as well as most of the magnetite, have disappeared, having been used by the large grains of new hornblende and plagioclase. In altered red beds from the area south of the "type section" (fig. 1), actinolite and hornblende have frequently begun to form before feldspathization set in. The hornblende of these rocks has the same optic properties as that of the "granodiorite-porphyry." Both the altered red bed sediments and the groundmass of the "granodiorite-porphyry" also show a felty or "fluffy" finely recrystallized variety free of, or poor in, clastic quartz grains. In the case of the red beds, the lack of such clastic grains is primary, and the same presumably applies in most cases where the "granodiorite-porphyry" has a similar groundmass.

I conclude that *the groundmass of the "granodiorite-porphyry" is not of igneous origin, but derived from the fine-grained clastic red bed sediments.*

(2) *Porphyroblastic nature of the apparent phenocrysts*

Superficial examination of thin sections of the "granodiorite-porphyry" shows apparent phenocrysts in the fine-grained

groundmass. Closer study reveals features which are incompatible with igneous phenocrysts, and suggest porphyroblastic growth in a solid rock. These features are especially well displayed by the *plagioclase*. Plate 3, fig. 1, shows a large composite plagioclase grain, and figure 2 a part of the same plagioclase under higher magnification. The plagioclase invades and absorbs the fine-grained groundmass, and it encloses its small quartz grains as relics. In other words, the groundmass was there before the plagioclase crystal formed. In its interior part, the plagioclase porphyroblast has succeeded in clearing itself of relict inclusions. In all thin sections examined, nearly all of the plagioclase grains exhibit distinct replacement borders of this type. Some plagioclases have preserved relict inclusions of the groundmass even in their interior parts (cf. pl. 4, fig. 1). Early stages of growth of plagioclase porphyroblasts are present in every thin section. The beginning of crystalloblastic growth of a plagioclase replacing the groundmass is shown in plate 1, figure 2. These early crystalloblastic patches are small, are often still turbid, and have ill-defined borders. A somewhat more advanced stage is seen in plate 2, figure 2. Plate 3 illustrates a much more advanced stage. The porphyroblast has become large, but it still lacks crystal form. Finally, crystal faces begin to develop, but relict inclusions of groundmass grains may still be preserved (pl. 4, fig. 1). If idioblastic crystals succeed in clearing themselves of inclusions, they imitate phenocrysts (pl. 4, fig. 2). This is the final stage of feldspathization. It must be stressed that in all thin sections examined which come from marginal as well as interior portions of "granodiorite-porphyry" outcrops, the various stages of development of plagioclase porphyroblasts occur together. Among the specimens collected, not one contains exclusively "good phenocrysts."

Although some incipient porphyroblasts of plagioclase are turbid, larger grains are usually clear, and only occasionally are turbid centers observed. Some plagioclase porphyroblasts are composite, and sometimes several grains are seen to coalesce which usually leads to complex twinning. Many of the large porphyroblasts show complex twinning, and it seems to me that this has to be chiefly attributed to coalescing. In some zoned crystals, coalescing has caused a complex arrangement of the zones. Occasionally, plagioclase porphyroblasts

enclose small grains of hornblende, biotite and sphene which had developed prior to feldspathization; it may be recalled that hornblende and occasional biotite also occur in some altered red beds.

The *potash-feldspar* crystals show the same replacement features and stages of development as the plagioclase. Potash-feldspar may form composite porphyroblasts with plagioclase, and occasionally with quartz. More commonly potash-feldspar encloses smaller plagioclase porphyroblasts, indicating that the optimum of potash-feldspar growth was somewhat later than that of plagioclase (cf. below). Apart from small relict grains of groundmass quartz, potash feldspar sometimes encloses small hornblende and titanite crystals.

The large *quartz* grains are also of a porphyroblastic nature although this is much less conspicuous than in case of the feldspar and, in fact, the quartz strongly suggests igneous phenocrysts upon superficial examination. Only exceptionally (pl. 7, fig. 1) do quartzes marginally enclose relict grains of the groundmass. This is understandable if it is realized that the high quartz content of the groundmass made it easy for a growing quartz grain to absorb the groundmass. Almost all of the large quartzes have sharp borders, and they often show those groundmass-filled embayments (cf. pl. 5, fig. 1, and pl. 7, fig. 1) which are so common in the quartzes of porphyritic acidic rocks and which are traditionally attributed to magmatic resorption. However, under higher magnification (pl. 5, fig. 2) the borders of all quartzes, including those having embayments, are seen to be surfaces of growth, with numerous delicate projections growing into the groundmass and absorbing it. Moreover, like the feldspar, the quartz shows all stages of porphyroblastic growth, beginning with small crystalloblastic patches in the groundmass, and ending with bipyramids imitating phenocrysts. A moderately early stage is illustrated by plate 6, fig. 1. This grain exhibits the same type of growth surface as the more advanced large grains. In plate 6, this grain is confronted with a clastic quartz grain of comparable size, occurring in an altered finely breccious red bed sediment. It seems plausible that some of the quartz porphyroblasts in the "granodiorite-porphyry" have started from such clastic grains exceeding the usual small grain size of the sediments. However, this cannot apply to the majority

of the quartz porphyroblasts since in the "type section" (fig. 1) most of the red bed sediments laterally prolonging the "granodiorite-porphyry" and enclosed in it, are fine-grained.

The features described suggest that the groundmass-filled embayments are caused not by magmatic resorption, but by *differential growth* of quartz crystals in the solid groundmass. Some portions of a porphyroblast grew faster than others, and relict groundmass is preserved between such crystalloblastic projections. Not all embayed crystals would by their shapes suggest this interpretation (cf. pl. 5, fig. 1; however, some of these quartz grains may be cut close and parallel to their surfaces and therefore not reveal the typical pattern). But other embayed crystals do have shapes suggestive of this interpretation, and occasionally embayed quartzes are so shaped as to constitute definite evidence of growth, in addition to the generally developed surface character indicative of growth (cf. above). Such a case is shown in plate 7, figure 1. Here a quartz porphyroblast has grown differentially, two neighboring crystalloblastic projections have developed crystal faces, and between them an embayment of relict groundmass has been left. It is obvious that magmatic resorption would have attacked the crystal edges. In other words, this is growth, not resorption. This reasoning is borne out by another part of the same quartz individual (pl. 7, fig. 1) which shows an irregular replacement border enclosing relict grains of the groundmass.

I would like to state briefly two general arguments against magmatic resorption of the quartz crystals described. First, it is hard to conceive how a residual magma exceedingly rich in silica from which the quartz-rich groundmass would have to be derived, could have resorbed earlier-formed quartz phenocrysts. Second, it is difficult to understand why magmatic corrosion should form narrow embayments instead of attacking the quartz crystals in a more uniform manner along their surfaces and first rounding off any crystal edges which might have been present. The only possible mechanism of magmatic formation of embayments seems to me to be mechanical cracking of crystals still surrounded by magma (due to a rapid change of physical conditions), flowing of magma into such cracks, and magmatic corrosion along such fractures. However, in the rocks here described, no such systematic relation-

ship between embayments and cracks exists, although later fractures which are widely present, occasionally happen to have followed embayments.

The texture of the subordinate mafics in the "granodiorite-porphyry" matches that of the felsic porphyroblasts. Both *hornblende* and *biotite* show all gradations from xenoblasts to perfect idioblasts. In their early stages, they penetrate irregularly, replace and enclose the fine-grained groundmass. Elongation parallel to the c-axis of the hornblende and the base of the biotite already asserts itself at this early stage. A tendency to develop crystal faces becomes visible quite soon. A comparatively early stage of porphyroblastic growth is illustrated by plate 8, figure 1. Poikiloblastic textures usually still survive when the grains begin to develop continuity and to form well-defined crystal faces. The tendency of the mafic porphyroblasts to develop continuity first in their marginal portions, results in crystals which, in an advanced stage of development, still contain relict grains of groundmass quartz in their central parts. Occasionally this tendency has led to the formation of idioblastic crystals with a hollow core filled by groundmass fabric.[6] In the final stage of porphyroblastic development, the mafic crystals completely clear themselves of relict inclusions. The result is perfectly euhedral and continuous hornblende and biotite crystals indistinguishable from true igneous phenocrysts. It must be emphasized that, as in the case of the felsic porphyroblasts, early and advanced stages of development of mafic porphyroblasts occur together in every specimen examined.

As supplementary evidence, a rock from a neighboring area may be briefly described which shows an *incipient stage of granitization of Sheku type*. It was collected about 8 miles southeast of the southeastern corner of the area shown in the map (pl. 9), in a mountain range extending south from a peak called Mat'oushan. Here Upper Triassic (Norian) marine shales and sandstones contain some smaller sill- or dike-like bodies of light-colored igneous-appearing rocks which resemble fine-grained diorite-aplites. The microscope shows several varieties most of which bear clear evidence of a metasomatic origin. The rock here described is illustrated in plate 8, figure 2. It consists of a

[6] Somewhat similar growth has been described (in plagioclase porphyroblasts) by G. E. Goodspeed (1937b, p. 1135).

typically clastic fine-grained matrix and a large amount of albite and a smaller amount of chlorite porphyroblasts. The groundmass consists of angular and subrounded clear quartz grains part of which show small growth projections. They are cemented by an interstitial mass chiefly composed of albite. Most of this cement belongs to small incipient albite porphyroblasts each of which surrounds a number of clastic quartz grains.

The albite (An 3) porphyroblasts show pronounced sieve texture, enclosing clastic grains of groundmass quartz as well as smaller grains of crystalloblastic chlorite. The albite grains have irregular outlines. There are incipient as well as more advanced stages of porphyroblastic growth, but the stage has not yet been reached at which crystal faces begin to form, nor do the albite grains attain the size which is shown by the large plagioclases in the rocks from the Sheku region. Many of the albite porphyroblasts have turbid centers often containing sericite, and clear margins. Others are altogether turbid. The chlorite occurs in xenoblastic grains forming irregularly shaped aggregates with crenulated borders which marginally penetrate the groundmass, as well as in individual porphyroblasts. The latter vary in size and are mostly xenoblastic, with crenulated borders, but some of the larger grains show idioblastic tendencies and develop a platy habit. Part of the chlorite is associated with sericite which is often concentrated in the interior of chlorite aggregates. The rock also contains amoebae-like grains of calcite. Some are small, others become porphyroblastic. Concentrations of calcite and chlorite occur together, indicating a larger admixture of dolomite in certain portions of the clastic sediment. Another specimen shows microgranitic textures formed by metasomatic replacement.

The original sediment was a very fine-grained highly argillaceous sandstone or siltstone, containing some carbonate. The chlorite is undoubtedly derived from the constituents of the original sediment. The large quantity of albite, on the other hand, cannot be of the same origin, because no normal argillaceous-sandy sediment has such a high sodium content. Sodium must have been introduced. It has reacted with the argillaceous material in the sediment. The result was albitization. Both the presence of chlorite as a mafic, and the association albite plus calcite (without formation of calcium-bearing plagioclase),

indicate that feldspathization has in this case taken place under very low temperature, corresponding to epizonal temperatures in regionally metamorphic rocks. We may speak of local low-temperature sodium-metasomatism in a fine-grained clastic sediment—an incipient stage of feldspathization of the type developed on a large scale in the Sheku region.

IV. GENETIC DISCUSSION OF GRANITIZATION IN THE SHEKU REGION, AND COMPARISON WITH OTHER TYPES OF STATIC GRANITIZATION

(a) *Summary of unusual features in the Sheku region*

The granitized bodies described show several remarkable features. (1) Owing to the practically undisturbed condition of the enclosing sediments, the process of static granitization is displayed in an unusually convincing manner. (2) This mode of origin can be demonstrated for the whole of the granitic masses and not only their marginal parts. (3) Metasomatic transformation has here taken place at a remarkably shallow depth. (4) The non-granitized sediments enclosing the granitized bodies do not show thermal metamorphism of regional extent as is common in other areas of static granitization, and recrystallization of the sediments at contacts is surprisingly restricted. (5) A sediment-derived groundmass showing clastic relict texture has in a rather uniform manner survived in all parts of the granitized bodies. (6) The granitized rocks, as a whole, show a surprisingly uniform character, and contacts are usually sharp.

Some of these items have been sufficiently discussed in chapters II and III, others will have to be elaborated below. Points (4) and (6) are rather unexpected in metasomatic granitization and could indeed be used as arguments against it, if the evidence of granitization in the Sheku region were less convincing. I shall try to show that these features, and also the features listed as (5), are due to special conditions in this region, essentially the shallow depth of granitization, combined with the nature of the original sediments and the lack of deformation.

(b) *Shallow depth of granitization*

The granitized bodies of the Sheku region occur in the "upper red beds" (cf. above). These are the latest Mesozoic sediments I have observed anywhere in Northwest Yunnan. The

scantily developed Tertiary formations are later than the granitized rocks here described (cf. chapter I).[7] In view of the intense folding which the "upper red beds" have suffered in wide parts of Northwest Yunnan, it is extremely unlikely that any Mesozoic formation younger than the "upper red beds" and older than their folding and their granitization, could have existed without having in some areas been preserved in synclinal cores.

Therefore, the depth at which granitization took place at Sheku can hardly have been greater than the thickness of that portion of the "upper red beds" which has been eroded above the granitized bodies. The red beds preserved west of Sheku are about two miles thick. The granitized rocks exposed near the floor of the T'aohuats'un valley (traverse shown in fig. 1, southern section) were formed about one mile below the highest preserved red bed member, but farther north (fig. 1, middle section) similar granitized rocks represent the highest preserved red bed member. The question therefore is: How thick was that part of the "upper red beds" which has been entirely eroded? No direct evidence is available. However, it seems reasonable that it could hardly have exceeded a mile or two, in addition to the two miles of "upper red beds" preserved. This estimate is borne out by some sections of "upper red beds" which I have observed in other parts of Northwest Yunnan, where the thickness does not exceed a few miles.

The depth of granitization at Sheku was approximately between one and three miles, if the present vertical range of exposure of more than one mile is taken into account, in addition to the estimated thickness of one to two miles of the entirely eroded red beds. For granitization on a regional scale, i.e. for the *making* of granitic rock, this is a shallow depth indeed. In most cases, regional granitization has acted at greater depths. Obviously, the depth at which granitic rock is *made* must not be confused with the depth of granitic intrusion, i.e. of the secondary emplacement of ready-made granitic rock which has acquired mobility and has, by mechanical means, risen from its place of origin (cf. the brief discussion on "rheomorphism" at the end of Part III).

[7] In the southeastern part of the area shown in pl. 9, occurs a volcanic formation which is probably Tertiary though it might be Cretaceous. It overlies moderately folded "upper red beds" with angular unconformity, and is certainly not older than the granitized rocks of Sheku.

(c) *Mineralogical-chemical balance of granitization*

A comparison of the mineral composition of the incompletely recrystallized red beds and of the "granodiorite-porphyry" at Sheku shows that here the principal chemical feature of granitization was *addition of sodium*. The subordinate amounts of hornblende and biotite are derived from the original sediment. Iron was supplied by the hematite which is responsible for the color of the red beds and has been made into magnetite in the altered red beds. Calcium and magnesium occur as carbonate admixed in the clastic sediment. Carbonate is also present in most samples of altered red beds, though part of the calcium has here gone into epidote, and in some specimens from south of the T'aohuats'un valley some (exceptionally all) calcium and magnesium have been absorbed by amphiboles. In the granitized rocks, all of the magnesium and most of the iron—except a smaller amount persisting as magnetite—have entered hornblende and biotite. Some of the calcium has been consumed by hornblende, but most of it has been used for the anorthite component in the plagioclase. Neither free carbonate nor epidote have survived in the granitized rocks. This is not surprising, in view of the very large amount of metasomatic plagioclase formed. A minor quantity of calcium was used in sphene to bind titanium.

Silica and aluminum are the main constituents of the quartzose-argillaceous sediment. A minor amount of aluminum was used for the subordinate biotite of the granitized rocks, and the hornblende also consumed a small quantity of aluminum. Most of the aluminum went into feldspar. Silica was available in excess. Where, as for instance in the hornblende and the oligoclase, more silica was required relative to aluminum than was present in the clay minerals of the sediment, it was provided by the clastic quartz grains. Most of these have been absorbed in areas occupied by mafic as well as feldspar porphyroblasts. Their silica has, in part, been used for the porphyroblasts, and in part been pushed out to contribute to the porphyroblastic growth of quartz. The minor amount of potash needed for the subordinate biotite was supplied by the argillaceous material in the sediment (adsorption of potash). This is confirmed by the occurrence of sericite and occasional biotite in incompletely recrystallized red beds. That hornblende and biotite of the granitized rocks are de-

rived from the original sediment, is borne out by the presence of these minerals in some of the altered red beds from the mountains south of the main traverse surveyed. In these rocks, actinolitic amphibole has formed prior to hornblende. It represents a stage when temperature was lower.

The granitized rocks contain large amounts of porphyroblastic plagioclase. The calcium needed for the anorthite component was provided by the original sediment (cf. above). The sodium required for the large amount of the albite molecule present, could not be supplied by the original rock, since no normal quartzose-argillaceous sediment is nearly that rich in sodium. Addition of sodium is evident. Apart from sodium, probably a smaller amount of potash was introduced, though part of the potash entering potash-feldspar was provided by the sediment (the very minor amount of biotite would not utilize all the potash present in the argillaceous sediment). In addition to the potash-feldspar in the groundmass cement, the large microperthite porphyroblasts strongly suggest addition of some potash. It would have been introduced at a late stage of granitization; for it has been shown above that the optimum of porphyroblastic growth of potash-feldspar was later than that of plagioclase, though there is a wide range of overlap in the time of formation of these two minerals.

Muscovite is absent in the granitized rocks, although the original sediment is rich in clay and often contains sericite where incompletely recrystallized. Biotite occurs only in minor amounts in the granitized rocks, most of the iron and magnesium being utilized in hornblende which requires less aluminum. Nearly all the aluminum of the original sediment has been used for the formation of feldspar. It is thus indicated that the originally alkali-deficient rock became, during granitization, saturated with alkali. In other words, the granitizing agent was characterized by an alkali excess, with sodium predominating. As the mineralogical-chemical balance shows, the plagioclase, and even the albite molecule, were not introduced as a whole, but essentially sodium was the only substance added in the process of plagioclase formation. The plagioclase porphyroblasts are the product of reaction between country rock and granitizing agent, and are therefore truly metasomatic. This is confirmed by their replacement texture.

(d) *Mechanism of introduction*

For synkinematic granitization, this question has been discussed in Part I of the present paper (p. 226). Fundamentally, the mechanism is similar in static replacement. The main difference is that the directional influence of active differential shearing on the movement of "solutions"[8] is absent in static metasomatism, i.e. in infiltration of a mechanically isotropic rock mass. Therefore, the granitizing fluids tend to spread out in a more irregular manner. Structures which are mechanically dead but are still present, may have a certain directional influence during static granitization. They are either primary, such as bedding or different composition of adjacent strata. Or they are secondary but pre-metasomatic, such as schistosity of rocks which were metamorphosed prior to their static granitization, or as fractures, crush zones and joints, the latter three having only a local directional influence. In the Sheku region, the irregular spread of granitization is very pronounced, because the infiltrated sediments are comparatively uniform in character, and have not acquired secondary anisotropy by intense deformation prior to granitization.

Another difference in static granitization is that there is no mechanical breakage of mineral grains which under conditions of synkinematic metamorphism and replacement facilitates the movement of solutions. On the other hand, under static conditions, the lack of tectonic compression would tend to make it easier for solutions to rise.

In Part I, certain general arguments were advanced in favor of transportation in "solution" of the introduced material, and it was suggested that dry diffusion is not the principal mechanism of long-range transfer although there are examples of its local action in crystal lattices. These argu-

[8] The term "solution" is here, as well as in Part I, used to indicate a mobile phase capable of moving through solid rocks. It is supposed to contain both volatiles, essentially water, and metals such as alkalies and silica. No implication as to the physical state of these mobile agents is intended. In case of metamorphism and metasomatism under lower temperatures, there will be "ordinary" aqueous solutions. At high temperatures applied under considerable pressures—particularly if temperature rises above the critical point—the behaviour of "solutions" will be modified, and it must also be taken into account that they do not occur as uniform bodies but infiltrate the country rock in an excessively thin intergranular film. It is reasonable to assume, and is supported by ample petrographic evidence, that the hotter these "solutions" are, the more active they become.

ments apply equally in the case of static granitization here described. The presence of at least some water during the process of granitization is also here demonstrated by the occurrence of hydrous minerals in the granitized rocks, apart from the fact that the original argillaceous sediments contained considerable amounts of water which were set free in the process of metasomatic feldspathization. It appears unlikely that rocks containing water could have been a suitable medium for dry diffusion as the sole or principal mechanism of long-range transfer.

Generally speaking, it seems to me that the concept of an active liquid phase, moving in an intergranular film, is supported by the microscopic study of both synkinematically and statically granitized rocks, especially if rocks showing incipient stages of granitization are studied. Most sections cut from such rocks clearly demonstrate intergranular activity including transfer of material; resorption of pre-existing crystals; reactions between original and introduced material; and the formation of new crystals. Dry diffusion as the principal mechanism would not be concentrated at the crystal boundaries, i.e. in the intergranular, but pass through the crystal lattices. As far as dry diffusion plays a role, it appears easier to conceive of it as a subsidiary mechanism which acts on a local scale in single crystals and small groups of crystals. Instances where microscopic textures suggest dry diffusion on the scale of single crystals, are numerous. An example given in Part I are statically recrystallized norites from the Nanga Parbat area in which crystalloblastic hornblende has penetrated calcic plagioclase, and this latter has near the hornblende been albitized, the plagioclase lattice remaining intact. The same process was observed in these rocks where crystalloblastic epidote penetrates calcic plagioclase. Among textures described from the granitized rocks of Sheku, the "pushing out" of surplus quartz from metasomatic plagioclase and other porphyroblasts suggests dry diffusion on a local scale. What has been said above about the mechanism of transfer, applies to shallow and moderately deep-seated metasomatism only; for the rocks used as evidence have formed at such depths (cf. also Part I). At very great depths, dry diffusion could more easily be the principal mechanism of transfer (cf. J. A. W. Bugge, 1945).

The location of the Sheku area of granitization seems to be determined by the regional structural pattern. As far as I have mapped Northwest Yunnan, much of this region is characterized by a northward divergence of orogenic trends, part of which is shown within the map (pl. 9). On the east, the trend is a little east of north, and on the west it is north-northwest. In the angle between these diverging compressive structures the "upper red beds" lack any strong deformation, but farther south they become involved in intense deformation and dynamic metamorphism, where the eastern and western structural elements finally converge. Because of this divergent pattern, the area of Sheku has not been compressed after deposition of the "upper red beds," and presumably this was the reason why here granitizing solutions rose more easily to high levels from the depths of the geosyncline, whereas they did not penetrate the highly compressed "upper red beds" farther south.

(e) *Substances transferred, and volume question*

As to the substances present in the granitizing solutions, I again refer to the discussion in Part I (p. 239-241). The general points made there also apply in the case of static granitization here described. The chief difference is that at Nanga Parbat the predominant alkali introduced was potash, whereas at Sheku it was sodium. However, both synkinematic and static granitization comprise examples of potash as well as of sodium predominance, and some intermediate cases. The differential character of granitization controlled by the composition of the country rocks, which has been demonstrated at Nanga Parbat, is not well illustrated in the statically transformed red beds of Sheku because they are comparatively uniform in composition. However, where static granitization has acted on rocks of highly varied composition, the principle of differential granitization is often as clearly displayed as at Nanga Parbat. An example is the area between Riverside and Conconully in North Central Washington (cf. Part III, chapter III).

As at Nanga Parbat, it can be demonstrated at Sheku that *the material added to the country rock did not have the composition of granite or granodiorite, nor even of feldspar. The essential material added was alkali.* In the metamorphic argillites of Nanga Parbat, *varying amounts of silica* were precipitated with the alkali. To what extent silica has been

added at Sheku, is not easy to ascertain because the red beds affected contain variable, usually comparatively large, amounts of clastic quartz. As far as silica has been precipitated, its amounts have been small. Silica—presumably in large part derived from quartz-rich members among the geosynclinal sediments—seems always to accompany the alkali in granitizing solutions. For in areas of granitization rocks which compared to granite or granodiorite were deficient in silica, have generally been able to obtain the silica required. No silica is precipitated in rocks high in silica, and the amount precipitated in other rocks depends on their needs, i.e. on their silica deficiency compared to granite or granodiorite.

The amount of alkali added in the granitized rocks of Sheku was several per cent. Considering the primary quartz content of the red beds, the *total amount of added material* hardly exceeded about five per cent. Equally small amounts have been added during the granitization of other quartzose-argillaceous sediments, if their original silica content did not differ much from that of a granite or granodiorite.[9] Argillites poorer in clastic quartz, i.e. relatively purer shales composed of clay minerals with an admixture of quartzose silt, and their metamorphic equivalents, on the other hand, contain less silica than granite or granodiorite. Many of these rocks need as much as 10 to 15 per cent of silica to become granitized. Thus, in rocks of the series argillite—quartz-rich argillite, the *amount of silica added during granitization varies* from about 15 per cent to zero. Sediments richer in silica than granodiorite or granite will during granitization undergo a silica decrease, either relatively, or absolutely, i.e. due to actual removal of silica. Obviously certain arkoses do not require any addition at all during their granitization.

As at Nanga Parbat, there is no sign in the Sheku region of substances having been *removed* from the metasomatized rocks (except water, cf. below) and precipitated in an outer aureole surrounding the granitized bodies. Generally speaking, it appears to me that *large-scale outer fronts* formed by precipitation of substances driven out from the country rock, are *frequently lacking* both in areas of synkinematic and of

[9] Quartzose-argillaceous sediments containing about 45 to 50 per cent quartz will require neither much introduction nor much removal of silica during their granitization.

static granitization, and that therefore the formation of a "basic front" cannot be considered as a *necessary* part or result of granitization. That this process *can* happen, has been demonstrated by Doris L. Reynolds (1946; 1947). In my personal field experience, I have observed *local* concentrations or segregations of mafic constituents which, compared to the size of the granitized bodies, are small—as a rule, extremely small—and could be described under the heading "local metamorphic differentiation."

In all granitized areas where addition is not compensated by removal of material, the *volume* of the transformed rock body obviously must have increased. However, as far as *granitization of argillaceous rocks* is concerned, increase of volume due to addition of material must be supposed to be to some extent compensated by loss of water which is set free during the metasomatic formation of feldspar from hydrous minerals such as clay minerals and micas. If a calculation is based on a mineral like kaolinite, the loss of water is considerable and, in per cent of weight, of the same order as the amount of alkali introduced. At the same time, the densities of clay minerals and alkaline feldspars do not differ much. It may therefore be supposed that in those quartz-rich argillites the original quartz content of which made addition of any larger amounts of silica during granitization unnecessary (cf. above), the increase of volume was negligible.

On the other hand, a calculation may be based on metamorphic hydrous minerals such as muscovite, i.e. the feldspathization of rocks may be considered which prior to granitization had undergone a thorough metamorphic recrystallization—a process which was accompanied by a decrease in volume implied in the alteration of sedimentary clay minerals like kaolinite to metamorphic minerals like mica (loss of a considerable part of the water, and somewhat higher density of the mica).[10] On this basis, i.e. considering formation of feldspar from a mineral like muscovite, the amount of water set free is much smaller, and is to some extent counteracted by the somewhat lower density of alkaline feldspars compared to that of micas. Therefore, the volume must have somewhat in-

[10] Such a slight decrease in volume will be difficult to ascertain, especially where the rock has at the same time been deformed, i.e. in phyllite or micaschist.

creased. It must not be overlooked that formation of alkaline feldspar from either clay minerals or mica implies consumption of additional silica. In quartzose-argillaceous rocks with a sufficiently high original quartz content, this silica is furnished by quartz grains which are consumed in the feldspar reaction. As has been shown above, the amount of additional silica required in granitization of rocks of the *series argillite—quartz-rich argillite*, varies from about 15 per cent to zero, depending on the amount of clastic quartz in the sediment, whereas alkali is introduced in all cases.

In areas where no removal of material other than water during granitization can be demonstrated, therefore only a negligible to moderately small increase of volume has to be expected in rocks of this series. The variation essentially depends (1) on the amount of silica which had to be introduced during granitization, and (2) on the kind of the aluminous minerals used for the making of metasomatic alkaline feldspar, i.e. whether an argillite was more or less directly metasomatized and metamorphic hydrous silicates, formed from clay minerals, only occurred as a transitional phase localized at the advancing front of granitization, or whether a previously metamorphosed argillite was granitized. In the quartzose-argillaceous sediments of Sheku, no large amounts of additional silica were needed during granitization (cf. above), and there had been no regional metamorphic recrystallization prior to granitization. Therefore, the increase in volume, if any, must have been extremely small.

In all those granitized rocks in which a noticeable increase in volume must be expected, such an increase will be more easily ascertained in an area of static than in one of synkinematic granitization. In the latter case, superimposed tectonic deformation tends to obscure structures which might be indicative of an increase of volume. Yet some features indicating increase of volume may be recognizable in areas of synkinematic granitization. In Part I, the structures of certain metasomatic gneisses at Nanga Parbat, such as augengneisses, have been interpreted in this way (p. 227). In addition, the regional structural pattern of the Nanga Parbat gneiss massif as shown in the map (fig. 1, Part I) suggests a certain increase of volume.

Among rocks commonly granitized in geosynclinal belts, the

argillaceous sediments just discussed range first. Second are *moderately basic and intermediate rocks* of either sedimentary or igneous derivation. The amount of material added during their granitization is larger, but in most cases ranges from about 25 to about 50 per cent. Rocks of this group are mostly granitized in areas of predominant sodium metasomatism. The products are therefore more often granodioritic and quartz-dioritic than granitic *sensu stricto*. The basic process is metasomatic formation of sodic plagioclase; the material used for it is in part derived from the country rock. Silica is also added. Its continued introduction sooner or later leads to precipitation of quartz. Where potash-feldspar is formed, usually it appears only at a comparatively late stage, and only sometimes in such quantities that the rock becomes granitic *sensu stricto*. As mentioned in Part I, potash metasomatism immediately applied to basic rocks, achieves only biotitization in the majority of cases. As to the volume balance in the granitization of moderately basic and intermediate rocks, either considerable quantities of material must be removed; a process which will be traceable in the field (I again refer to Doris L. Reynolds' "basic fronts"). Or the volume of the granitized body must be considerably enlarged; structural evidence of which detailed field work can hardly fail to produce, especially if transformation has been static.

Granitization of *highly basic and ultrabasic rocks* is rare but does occur. Granitized bodies of this derivation are usually small. Where I have seen transformation of rocks of this group, frequently gabbroid and dioritic stages intervene, but there also seem to be cases of direct introduction of alkali feldspar. In granitized rocks of this group, the added material very commonly exceeds the original material. Removal of part of the original material will be the rule.

(f) *Temperature of granitization, mechanism of heat introduction, and "contact action"*

The granitized rocks of Sheku were formed at a fairly high temperature, corresponding approximately to temperatures in the middle zone of regional metamorphism, and presumably its hotter part. This seems indicated by the mineral association of calcic oligoclase, microperthite, hornblende and biotite. As far as my field observations go, temperature

nowhere seems to have become high enough to permit the granitized material to flow. In connection with the temperature of metasomatism at Sheku, it is of interest to recall that southeast of this area local sodium metasomatism has taken place at a much lower temperature, corresponding to that in the epizone of regional metamorphism (cf. p. 390-392). There are other examples of low-temperature feldspathization recorded in the literature. Among them the metasomatism of a coaly sediment described by G. E. Goodspeed, R. E. Fuller and H. A. Coombs (1941) from near Mount Rainier is of particular interest. All cases of feldspathization at very low temperatures seem to be local. Regional granitization appears always to be connected with higher (at least "mesozonal") temperatures, as the mineral assemblages suggest.

The heat required for granitization was transported by the granitizing fluids. What in Part I (p. 241-244) has been said about this point in case of synkinematic granitization, also applies here. In the Sheku region, the identity of the chemical and the thermal agent of granitization is even more obvious. For wherever the sediment has been supplied with the chemical substances required for granitization, simultaneously enough heat has been introduced to allow the characteristic mineral assemblage to form. On the other hand, there has been no perceptible regional increase of temperature in the rock masses not reached by the granitizing agent. Even in the immediate vicinity of granitized bodies, temperature fell off rapidly. Along contacts, the red beds have only been incompletely recrystallized and show, for the most part, a low-temperature mineral assemblage. Moreover, the zone of altered red beds is in most places narrow and sometimes altogether absent. The *rapid decrease of temperature at the contacts of the granitized bodies* is surprising and, in comparison with most granitized areas, unusual. It appears to me to be due to the remarkably shallow position of the granitized bodies in this region (cf. above, chapter IVb), as a result of which heat distributed by conduction was lost very rapidly. Only where hot granitizing solutions spread laterally, would heat not have so easily escaped from beneath metasomatized bodies thus formed, and wider "contact zones" could thus have originated (as probably at the peak 17,000′ in pl. 9).

Most areas of static granitization show evidence of *regional increase of temperature* in the country rocks which have thus been more or less completely recrystallized (hornfelses and related rocks, showing high-grade and more often medium-grade mineral assemblages), if they had not been altered to crystalline schists during preceding orogeny. The distribution of temperature in the Sheku region illustrates that regional heating cannot be considered as primary and static granitization as an ultimate result, but that the reverse relationship exists. This argument does not apply at very great depths where no introduction of heat is required to reach high temperatures. At very shallow depths, very little regional heating may be achieved outside the actually metasomatized rocks. At Sheku, the metasomatizing fluids must initially have been rather hot, and their upward migration must, in terms of geologic time, have been rapid, and there must for some time have been a continuous supply of these hot fluids. Otherwise the great differences in temperature deduced above could neither have been produced, nor have been maintained for some time. Perhaps additional heat was created by chemical reactions after the process had been started by the granitizing agent.

(g) *Preservation of relict textures, and porphyritic-appearing versus eugranitic-appearing textures*

In the groundmass of the granitized rocks of Sheku, a sedimentary relict texture has been preserved. Survival of pre-granitization textures and mineral grains is common in granitized bodies, and usually much more so in their marginal than in their interior portions. Pre-granitization textures more often survive in statically transformed rocks, whereas they are more likely to be destroyed by differential deformation in synkinematically granitized rocks. In this respect, the survival of relict textures in the rocks of Sheku is not surprising. What is unusual is that these relict textures are clastic, and that they have survived throughout the transformed rock bodies.

The preservation of clastic textures is obviously due to the lack of regional heating and consequently of regional thermal metamorphism of the red bed sediments outside the bodies actually reached by the granitizing agent. This feature

has been treated above, and has been attributed to the unusually shallow depth of granitization at Sheku. As a rule, in areas of large-scale static granitization, sediments are more or less thoroughly recrystallized as hornfelses and related rocks, and it is therefore the textures of these rocks which are preserved as relics in the granitized rocks, and not the original sedimentary textures which seldom survive in thoroughly recrystallized rocks, although sedimentary structures such as bedding, lamination, etc., are widely preserved in the recrystallized rocks and can sometimes be traced into the granitized rocks. Where static granitization has affected rocks which had previously been subjected to orogenic regional metamorphism and thus become crystalline schists, their schistosity often survives in the granitized rocks as a relict structure which gradually becomes fainter and fainter and may finally disappear (J. J. Sederholm's "nebulites"). At Sheku, the red bed sediments were neither regionally hornsfelsic nor schistose, and therefore their original sedimentary texture was inherited by the statically granitized rocks.

The preservation of a relict groundmass between newly formed porphyroblasts, is responsible for the *apparent porphyritic texture* of the granitized rocks of Sheku. Similar textures often occur in granitized rocks. If the process was synkinematic, such textures are seen in porphyroblast-schists and augengneisses. If replacement was static, textures of a more typically porphyritic appearance are displayed by feldspathized hornfelses, etc., and sometimes by feldspathized rocks still possessing sedimentary relict textures. However, in the majority of cases, such porphyritic-appearing rocks occur in the marginal parts of statically granitized bodies, and larger bodies usually develop less uneven-granular and more *"eugranitic"-appearing textures*, especially in their interior parts. The lack of such eugranitic-appearing textures in the metasomatized red beds of Sheku is remarkable. I would attribute it both to the shallow depth, at which the granitized rock became rapidly cooled after the metasomatizing solutions ceased to rise from below, and to the originally fine-grained and subsequently poorly recrystallized nature of the sediment subjected to metasomatism; the low degree of recrystallization was also due to shallow depth. It seems obvious that in a less fine-grained sediment, and particularly in a thor-

oughly recrystallized rock like a hornfels, feldspathization combined with more coarse-grained recrystallization of non-metasomatized minerals, will more easily achieve a eugranitic-appearing texture, than in a rock composed of very small clastic quartz grains cemented by altered argillite material.

Generally speaking, we may contrast *transformation of the Sheku type* with a "*normal type*" *of static granitization.* The type of Sheku is less complete—not in a chemical but in a textural sense—and lacks regional heating of the non-metasomatized country rocks. Both features are chiefly due to the shallow depth of formation. The "normal type" produces more evenly medium- or coarse-grained granitic and granodioritic rocks, and regional heating of the non-metasomatized country rocks is in most cases evident.

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(*To Be Continued*)

SPHEROIDAL WEATHERING OF IGNEOUS ROCKS

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ABSTRACT. Spheroidal weathering is that process by which igneous rocks scale off in concentric shells producing rounded boulder-like forms. Despite recent observations and experimental data, many individuals still misunderstand the true nature of this process. The present paper is an attempt to clarify the matter.

The first part of the paper reviews the several hypotheses which have been advanced from time to time to explain spheroidal weathering. The current views, held by the best authorities, are that spheroidal weathering results from either of two processes: (1) the swelling and spalling of the exterior surface of angular blocks of rock due to the hydration, carbonation, and oxidation of constituent minerals in the outer surface, or (2) the swelling and spalling of the exterior surface of angular blocks which have been subjected to sudden, intense heating of their exterior by forest fires and brush fires.

The second part of the paper describes the mineral alterations observed in the shells surrounding several spheroidally weathered boulders. This study shows that in general the core of each boulder consists of relatively fresh rock, but in the shells surrounding the core the primary minerals are altered by weathering to secondary minerals such as kaolinite, sericite, montmorillonite, serpentine, chlorite, hematite, and limonite. As a result of these changes the altered rock has increased in volume, the rock in the outer shells having suffered a greater increase than that in the inner ones. It is concluded that this increase has caused the rock to scale off in concentric shells.

INTRODUCTION

IT is a commonly observed fact that many igneous rocks tend to scale off along joint faces, especially at corners and edges formed by intersecting joints, and thereby develop rounded boulder-like forms which are often but not always enclosed in concentric shells. These rounded boulders range in diameter from a few inches to several feet, and the shells that bound them are from a fraction of an inch to several inches thick. The outer shells normally show a greater degree of weathering than the inner ones, and the core generally consists of fresh, unaltered rock. These boulders have been observed both at the surface and below the surface down to a depth of approximately 40 feet. Examples of this type of weathering have been reported from such widely scattered localities as California, Montana, Vermont, Oklahoma, Hawaii, Ireland, India, and Southern Rhodesia.

The term "exfoliation" has been applied by various writers

to this phenomenon, a word which can be traced to the Late Latin *exfoliare* which means to strip of leaves or to scale or flake off. This term has lost much of its significance, however, since it has been applied in a general way to several types of rock spalling, such as the flat flaking of the pyramids in Egypt (Barton, 1916); to sheeting which is flaking on a much grander scale (Gilbert, 1904; Miller, 1911); and to the type of rock spalling that develops rounded residual boulders (Grabau, 1920, pp. 393-394; Blackwelder, 1925). Other names such as "concentric exfoliation," "concentric weathering," and "spheroidal weathering," have also been applied to the process by various authors. The present writers believe that the term spheroidal weathering is the most appropriate for this type of weathering, since it is expository and describes the type of boulder that is formed by the process. This name, therefore, will be used in the present paper.

During the last 90 years several hypotheses have been advanced to explain the spalling of rocks to produce rounded forms. It appears certain now, however, largely as a result of the careful studies of Eliot Blackwelder (1925, 1926), that spheroidal weathering results from the swelling and spalling of the exterior surface of blocks of rock due either to: (1) the hydration, carbonation, and oxidation of constituent minerals in the outer surface, or (2) the sudden intense heating of the outer surface by forest fires and brush fires. The senior author of the present paper has observed, however, in discussing the matter with others, that in spite of Blackwelder's work some geologists and many students are still confused by spheroidal weathering. Many fail to appreciate the relative importance of the two processes involved or are unable to discern which process operated in a particular case. The confusion is increased by the use of the name "exfoliation" for this type of weathering, a term that has also been applied to other somewhat similar processes. The purpose of the present paper is to clarify the subject and dissipate some of this confusion.

The first part of this paper is an historical review of the several hypotheses that have been advanced to explain the phenomenon of spheroidal weathering. The development of ideas is traced and the current views on the process are summarized. The second part of the paper is a description of the

actual mineral alterations that have taken place in the shells surrounding several spheroidal boulders. It is believed that this information is a worthwhile contribution inasmuch as heretofore the mineral alterations accompanying spheroidal weathering have been described rather generally and vaguely, and, so far as the authors are aware, no detailed microscopic description of such changes has ever been published.

Development of Hypotheses on the Origin of Spheroidal Weathering

Many years ago Page (1861, p. 75) in connection with his studies on the structures of igneous rocks, noted that some greenstones present a spherical or globular structure, the weathered cliffs of such a rock appearing like a huge accumulation of bombs and balls varying from a few inches to several feet in diameter. "Such a structure," he said, "from its apparent aggregation round a common centre, is also termed concretionary, and generally exfoliates, on exposure to weather, film after film, like the coats of an onion." Page evidently thought that the spheroids produced by weathering were fundamentally concretionary in nature and were merely brought out by weathering.

Bonney (1876) related that Professor J. Thompson regarded spheroidal "structure" as "the result of a process of exfoliation due to the action of the weather on a tolerably regular-shaped, homogeneous mass" (p. 149) along joint planes. Bonney disagreed with Thompson, however. He was willing to concede that cuboidal blocks of rock obviously tend to weather into rough spheroids; also that further action of the weather might occasionally produce concentric exfoliation in such spheroids; however, he did not believe that any theory of decomposition was adequate to explain the facts. Bonney believed that spheroids could form without the presence of joint planes. He supported his argument by citing the columnar basalt near Le Puy, Central France, in which "spheroids may be seen, . . . enclosed three or four at a time in a columnar shell without any dividing cross joints, so that they are just like Dutch cheeses packed in hexagonal cases (the interstices being filled up). The lid of the box has more or less fallen away and exposed the contained spheroids." (p. 150). He pointed out that since these spheroids are all solid, weathering

has not occurred because there are no joints along which it can proceed. Bonney was convinced that spheroidal "structure" is due chiefly to contraction of the mass while cooling. During the discussion which followed the presentation of Bonney's paper before the Geological Society of London, a Mr. Koch told of an experiment in which he had placed fragments of ironstones and quartzite upon the sole of a furnace. These fragments cracked off in shells, leaving spheres. Thus Bonney's paper considers three hypotheses for the origin of spheroidal weathering: (1) Professor Thompson's theory of chemical decomposition caused by weathering along joint planes; (2) Bonney's theory that spheroids are the result of contraction of the rock mass while cooling; and (3) Koch's discovery that spheroids may be produced by the heating of rocks.

Geike (1882, p. 335) interpreted the spheroidal boulders of igneous rock as a result of weathering. He observed that: "In many prismatic massive rocks (basalt, diorite, etc.) segments of the prisms weather into spheroids, in which successive weathered rings form crusts like the concentric coats of an onion. When one of these rocks has been intruded as a dike, it sometimes decomposes to a considerable depth into a mass of brown ferruginous balls in a surrounding matrix—the whole having a resemblance to a conglomerate made of rolled and transported fragments."

Along the Potomac River, outside of Georgetown, Washington, D. C., Spencer (1885) noticed perfectly rounded boulders of gneiss in a large mass of decayed rock of similar composition. The hillside had been cut away in the construction of a road beside the river, and exposed decayed crystalline rock to a depth of nearly 50 feet. Much of the gneiss was disintegrated but contained unaltered masses which had resisted atmospheric decay. Some of the gneiss upon weathering exhibited a schistose structure, yet much was remarkably compact, but traversed by numerous joint planes extending in all directions. As the weathering proceeded from the joint planes it left solid masses which were spheroidal and often showed a banded structure. Surrounding them were concentric zones which he decided marked the progress of decay and were in no way related to concretionary structure.

Thus far, geologists had noted spheroidally shaped boulders,

enclosed in a series of concentric shells which they believed were caused by weathering, but they had not explained the mechanics of the process.

The importance of oxidation and decay in the production of spheroidal weathering was first clearly outlined by Dana (1895, p. 127). According to him: "This oxidation process, and other methods of decay go on with greatest rapidity in the fissures of rocks below a surface soil, because the descending surface waters keep them almost continuously wet; and it is under such circumstances that a rock which is much fissured or jointed becomes reduced to a pile of great boulders with a rusty earth between. The decay of oxidation at first produces a thin discoloring of adjoining surfaces, and this continues, eating off the angles, which are attacked from three directions, until a bluff of solid rock becomes apparently a pile of great boulders. With the progress of alteration, the discolored portion becomes banded with yellow and brown; and as it deepens, the outer part of the spheroid sometimes separates in concentric shells, precisely corresponding with the concentric structure of a concretion. But these concentric shells are due to the decay that is in progress; and apparently to alterations in the work of decay dependent on climate . . . " Dana thus recognized that this spheroidal weathering is due to a definite type of chemical action related to climatic conditions.

The "niggerheads" of the gabbro area around Baltimore, Maryland, were cited by Merrill (1897, pp. 241-248), as typical examples of spheroidal weathering. These massive rocks, he thought, had been originally traversed by one or more sets of joints, along which moisture and "the accompanying agents of disintegration" had made their way and gradually rounded off the corners until only an oval mass remained, surrounded by concentric layers. Merrill believed that the above process holds true also for huge granite bosses, or domes, such as those in Yosemite Valley, California, and Stone Mountain, Georgia. These domes, he felt, were merely on a much grander scale. He did not elaborate upon the mechanics of the process.

Some years later J. F. Kemp (1909) received from a Mr. J. R. Villars a photograph accompanied by a letter discussing the curious weathering of a diabase dike near Butte, Montana.

This dike, which was exposed to a depth of 20 or 30 feet, showed rounded masses of rock varying in diameter from a few inches to two feet. These masses were separated into concentric layers, a division which was marked in the weathered rock but was wanting or scarcely observed in the fresh rock. Kemp forwarded the photograph and letter to the Mining and Scientific Press stating that: "The dike is a fine illustration of spheroidal weathering . . . the breaking up being in large degree referable to strains produced in cooling. Weathering has brought out the shelly or onion structure, but one cannot well resist the conviction that some internal structure has facilitated the assumption of these peculiar shapes." (p. 443). Although Kemp's conclusions are not at all clear, it appears that he attributed spheroidal weathering of the diabase to a combination of three factors: (1) internal structure, (2) strains caused by cooling, and (3) weathering.

Hobbs (1912, pp. 150-152) was one of the first to recognize two distinct processes in the development of rounded boulders resulting from spheroidal weathering: (1) mechanical disintegration, and (2) chemical decomposition. Hobbs believed mechanical disintegration is due to daily temperature changes. Relative to chemical decomposition he made an effort to analyze its progress. He stressed the importance of jointing in facilitating the progress of chemical decay which he thought was brought about by the process of hydration and carbonation. He emphasized that the newly formed minerals, resulting from hydration and carbonation, are notably lighter and hence more bulky than those minerals from which they have formed. "Strains are thus set up," he argued, "which tend to separate the bulkier new material from the core of unaltered rock. Eventually, the squared block is by this process transformed into a spheroidal core of still unaltered rock wrapped in layers of decomposed material . . . " (p. 151).

Cleland (1916, pp. 31-33, 39-40, 388), like Hobbs, believed that rounded boulder-like forms can be developed by two distinct processes of weathering. One of these he termed "spheroidal weathering" which he considered to be brought about by chemical decomposition occasioned by hydration. The other he called "exfoliation" and explained it as mechanical disintegration brought about by daily changes in temperature.

Grabau (1920, pp. 393-394) believed that rounded boulders

are produced in two ways: (1) by "concentric exfoliation" whereby the rock peels off in concentric shells, and (2) by granular disintegration whereby the rock crumbles into grains but leaves a rounded residual boulder. "Concentric exfoliation" he attributed to daily changes of temperature. These changes, he maintained, are especially great in desert regions and have been estimated on the surface of some rocks to be as great as 80°C. The rock, being a poor conductor of heat, is affected chiefly on the surface, although the heat passes inward very gradually. On cooling by radiation in the clear atmosphere, the temperature of the outer layers sinks rapidly and easily passes below that of the inner part of the rock. As a result, the surface portion, for some distance inward, is subjected to a series of stresses which results in the flaking or peeling off of the outer layers. Since the angles of the rock are most exposed, being subjected to heating and cooling from all sides, they peel off first and the result is the production of curved and rounded outlines. Thus, according to Grabau, "concentric exfoliation" or the successive peeling off of layers results, a phenomenon very marked in most dark and fine-grained igneous rocks in desert regions. Grabau illustrates this process by a photograph showing what he calls "concentric exfoliation" in a dike of basic igneous rock taking place at a depth of at least 25 feet below the surface. Most people today would agree, however, that temperature changes are insignificant at such depth. Furthermore, the surface of the ground shown in this photograph is covered by rather dense vegetation, indicating that the climate is reasonably moist and not arid as intimated.

The other process that Grabau believed effective in the development of rounded boulders is granular disintegration, which he attributed also chiefly to daily temperature changes. This process may operate in three different ways: (1) Since different minerals, such as plagioclase and pyroxene, for example, have different coefficients of expansion and contraction, internal stresses are set up in the rock which tend to separate these minerals, one from the other, until a loose sand results. (2) Individual minerals themselves are affected by temperature changes due to the fact that they expand and contract differently in different crystal directions. The stresses thus set up tend to open up minute cracks along cleavage planes into

which air and moisture can penetrate and effect decomposition of the mineral. (3) "In moist climates, dark igneous rocks are often reduced to a mass of residual boulders by combined disintegration and decomposition." (p. 397).

The first systematic study of spheroidal weathering was made by Blackwelder (1925) who used the term "exfoliation" for the process. He pointed out that exfoliation, or the development of spheroidal forms, takes place most commonly in the granitoid igneous rocks, and occurs under various conditions. Blackwelder read some 30 standard reference works and special papers on weathering and decided that the majority of writers attributed exfoliation to the daily range of temperature in deserts and on mountain tops where the range is exceptionally great. As a result of intensive field work, however, he concluded that exfoliation is not a simple process, but a combination of processes of diverse origins.

In typical exfoliation, according to Blackwelder, "a series of cracks is formed roughly concentric to a single joint-block . . . The force producing the cracks has been one of tension, with the effective component operating in a radial direction . . . Such radial forces originate either by (a) the internal shrinkage of the block (b) by its external expansion" (p. 794).

In order to test the hypotheses of some writers that temperature changes cause exfoliation, Blackwelder made laboratory experiments in which he subjected sound igneous rocks to sudden changes of temperature, ranging from 15° to 210°C., by plunging the cold rock into boiling oil. In no case did these cause any spalling or cracking or even visible weakening of the rock. Inasmuch as this laboratory range in temperature is greater than any possible temperature range in the desert, the apparent lack of effect is significant.

From field observation Blackwelder noted that rocks in very dry deserts are rarely exfoliated. He examined hundreds of boulders strewn over the great alluvial fans in the Panamint and Salton deserts of California. He climbed many mountain peaks, 1000 feet to 3000 feet above timber-line, but found no evidence of exfoliation. In the humid climates, however, where the diurnal range of temperature is less than in the desert, he found that exfoliation appears abundantly in outcrops of granite, gabbro, and diabase. Furthermore, in these moister regions he found boulders of exfoliation forming at a depth of

20 feet below the surface. He considered these observations as cogent evidence that exfoliation is due to chemical decay.

A year later Blackwelder (1926) pointed out that in the semi-arid forested mountains of western United States fire seemed to rank first in causing the disruption of boulders and rock outcrops. This statement was supported by a series of experiments in which Blackwelder subjected different kinds of igneous rocks to repeated sudden heatings and coolings with temperatures ranging from 200° to 800°C. There was no visible effect upon the rock unless it approached the extreme temperature range that the rock was capable of withstanding. From these experiments Blackwelder concluded that insolation, or diurnal changes of temperature, are entirely inadequate to cause rock breakage. However, since the temperatures of fires are likely to reach 1200°C. and even above, he believed that forest fires can cause rocks to spall. He stated: "The field evidence is abundant, but has received little notice. On the broad plateau of the Medicine Bow Mountains, as well as in the Sierra Madre and other ranges in southern Wyoming, the writer has found nearly every boulder and outcrop in the forested zone thus cracked and rounded and the adjacent ground strewn with spalls. The effect of all other weathering processes were insignificant in comparison with those of the repeated conflagrations. Similar conditions were noted along the semi-arid eastern flank of the Sierra Nevada in California. In such localities it is probable that fire spalling demolishes exposed rocks much more rapidly than the more common but less violent processes such as chemical disintegration." (p. 138-139).

Like Blackwelder, Grout (1932, pp. 305-307) believed that the change in rock volume caused by daily and seasonal temperature variations is small in comparison with that resulting from forest fires, though the alterations caused by the former are more numerous and may have an effect over a period of years. He believed that: "the spalling produced by a single forest fire is probably comparable to the effects of sun and frost for a thousand years, though the great effect of fire may be partly a result of previous loosening of the grains by frost and other agencies."

The experiment by Griggs (1936) was designed to test the effectiveness of fatigue in rock exfoliation by insolation. Al-

though this experiment dealt with the process of exfoliation in the general sense, the results are significant with respect to spheroidal weathering. Griggs subjected a specimen of granite to artificial temperature changes in a 15-minute cycle varying from 32°C. to 142°C. This experiment was continued for the equivalent of 244 years of diurnal temperature change. Photomicrographs of the surface of the rock before and after the experiment showed that there had been no cracking or spalling as a result of heating and cooling. Griggs concluded that "the effect of temperature changes over a thousand years is not sufficient to cause any exfoliation or disintegration of granite" (p. 796).

The importance of fire was further emphasized by Emery (1944) who investigated the relations of brush fires to rock exfoliation. He studied several square miles of brush and grass land in San Diego, California, where he found that exfoliated rock outcrops are numerous. He observed that: "Spheroidal shapes are characteristic of quartz diorite outcrops in the region and further development of these shapes resulted from the exfoliation by the fire, since the thickest spalls were generally formed at the sharpest corners. Loosely attached to a few of the rocks were older but very similar spalls, suggesting that the spheroidal shapes of the rocks were partly due to previous brush fires . . . Since the heat even of a brush fire can produce extensive exfoliation, and, since large areas of the west have a brush cover, it seems not unlikely that a great deal of exfoliation has resulted from brush fires, with the consequent tendency toward development of spheroidal rock shapes in widespread areas" (p. 508).

Very recently Larsen (1948, pp. 114-119) described and illustrated some granitic rocks in Southern California that have weathered into rounded forms which he called "boulders of disintegration." These boulders are commonly buried 10 to 20 feet below the surface where they are imbedded in a gruss of disintegrated rock. The boulders themselves are fresh and some are surrounded by shells of fresh or partly decomposed rock. Many boulders now project above the surface or lie upon the surface. Larsen believes that at one time these were imbedded in gruss and later the intervening gruss was washed away leaving the boulders on the surface. He made chemical analyses of the fresh boulders and of the gruss surrounding them and from

Figure 1. Spheroidal weathering in porphyritic olivine basalt at the north end of the Koolau Range, Oahu. This exposure is in a steep cut and about 30 feet below the ground surface. Note that the spheroids are arranged more or less regularly in vertical and horizontal rows determined by joint planes. Some vertical joints are still visible. The spheroid in the extreme lower left corner is about 18 inches in diameter.

Figure 2. Detailed view of spheroidal weathering of porphyritic olivine basalt at the north end of the Koolau Range, Oahu. Note how the firm, unaltered rock in the interior of the spheroids grades radially outward through weathered shells into completely disintegrated rock.

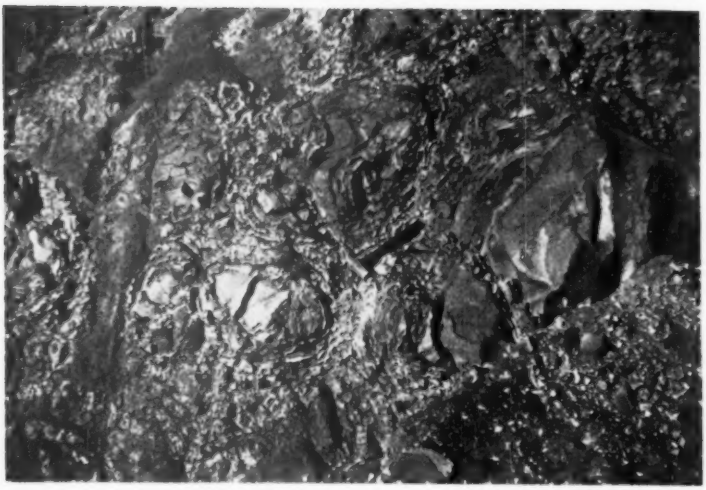

Figure 3. Spheroidal weathering in vesicular basalt on the Schofield Plateau near the west gate of Wheeler Field, Oahu. This outcrop is in a road cut about 12 feet below the ground surface. Note how weathering has taken place along joints which are less regular than in Figures 1 and 2.

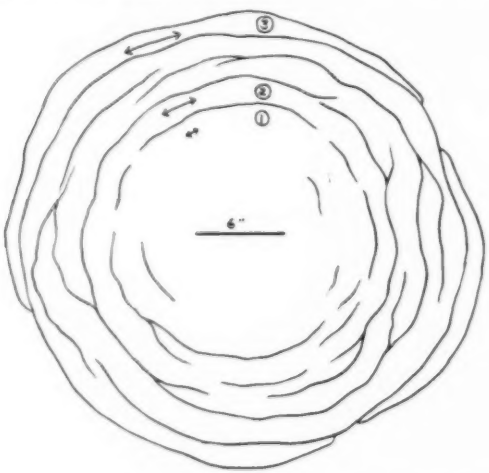

Figure 4. Hypothetical cross section through the boulder of porphyritic olivine basalt described in the text, showing the approximate location of the three specimens chosen for microscopic study. Specimen 1 is essentially unaltered except for slight serpentinization of the olivine phenocrysts. Specimen 2 is more weathered, with labradorite crystals altering to montmorillonite, and rims of iddingsite around olivine phenocrysts changing to limonite. Specimen 3 is badly weathered; labradorite crystals have been completely converted to montmorillonite and augite crystals and iddingsite rims are clouded with limonite. The arrows indicate the direction and relative intensity of the expansive force in each layer resulting from alteration of the rock. These expansive forces have caused the rock to scale.

Figure 5. Spheroidally weathered boulders of biotite granite near U. S. Highway 287, about 5 miles south of Virginia Dale, Colorado. Although this is a semi-arid region, temperature variations are not extreme and the shelling of the exterior is due to decomposition and not to temperature changes.

Figure 6. An especially fine specimen of spheroidally weathered biotite granite along U. S. Highway 287, about 5 miles south of Virginia Dale, Colorado. This boulder is a residual that remains after the surrounding rock has weathered away. Microscopic examination reveals that the minerals in the outer shells are more altered than those in the inner ones and that spalling is due to chemical decay.

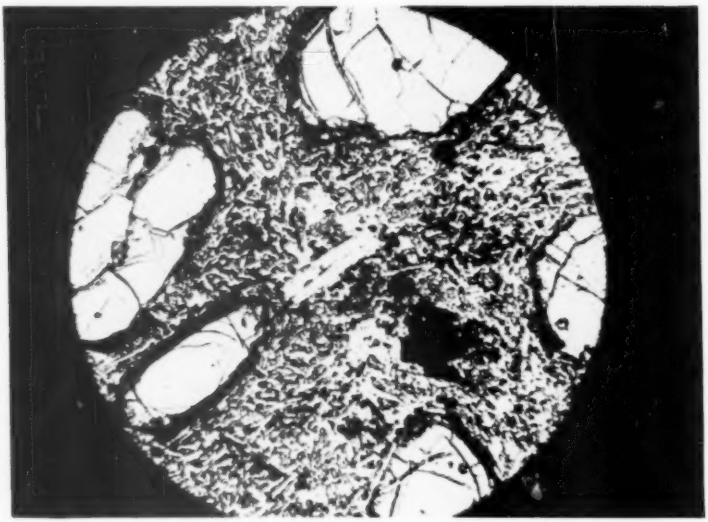

Figure 7. Photomicrograph of slightly weathered porphyritic olivine basalt (specimen 2) from the innermost shell of a spheroidally weathered boulder. This specimen shows slightly more alteration than the fresh basalt (specimen 1) of the interior core. The iddingsite rims about the large phenocrysts of olivine have become nearly opaque by alteration to limonite. In the groundmass the crystals of augite (high relief) and magnetite (black) remain fresh, but the centers of many labradorite crystals (white and lath-shaped) have altered to montmorillonite. Photomicrograph taken in plane polarized light. Diameter of field about 3 mm.

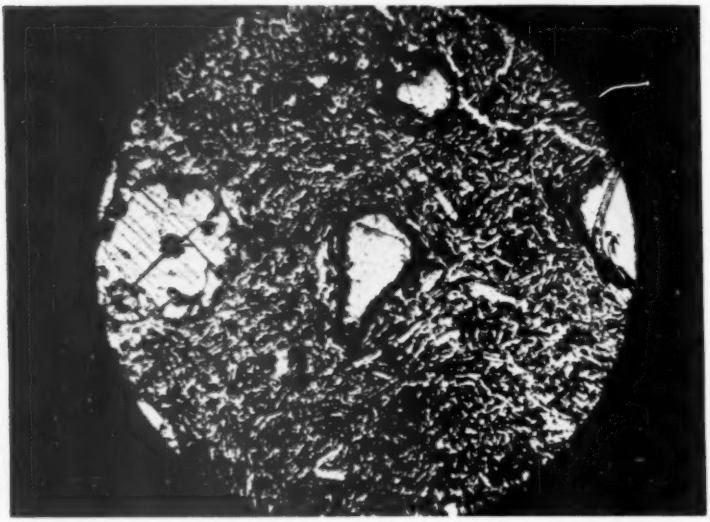

Figure 8. Photomicrograph of badly weathered porphyritic olivine basalt (specimen 3) from the outermost shell of the same spheroidally weathered boulder mentioned in Figure 7. The iddingsite borders on the phenocrysts of olivine are completely oxidized to limonite. The major alteration has been in the groundmass where the augite crystals are now permeated with tiny specks of limonite, making them nearly opaque. The labradorite crystals, although retaining their outlines, have been converted to a lamellar aggregate of montmorillonite. Photomicrograph taken in plane polarized light. Diameter of field about 3 mm.

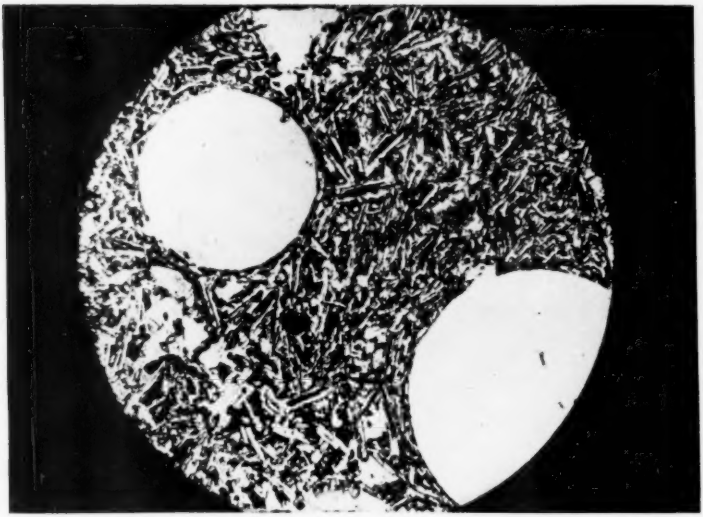

Figure 9. Photomicrograph of relatively fresh vesicular basalt (specimen 4) from the periphery of the interior core of a spheroidally weathered boulder. The rock consists of well-rounded vesicles and a groundmass of labradorite (white laths, some with dark interiors), augite (somewhat clouded, irregular and elongate grains with high relief), magnetite (black grains), and interstitial glass (small colorless areas). The interiors of some labradorite laths are slightly saussuritized and some augite crystals are clouded by limonite. Photomicrograph taken in plane polarized light. Diameter of field about 3 mm.

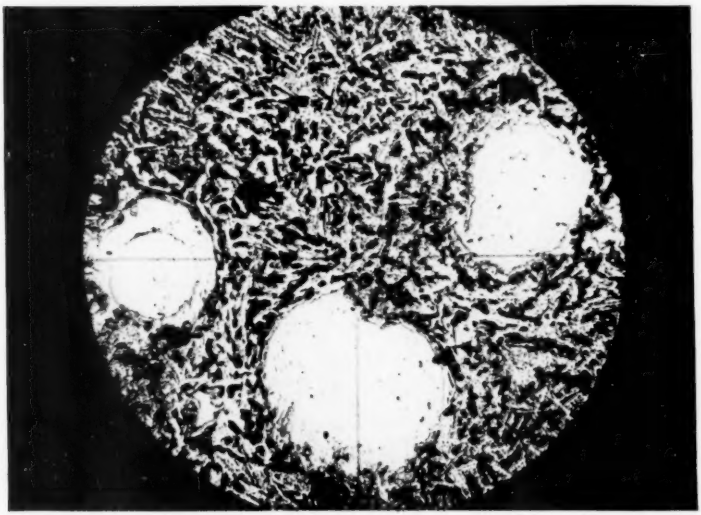

Figure 10. Photomicrograph of weathered vesicular basalt (specimen 5) from the outer shell of the same spheroidally weathered boulder mentioned in Figure 9. Here the augite crystals are badly decomposed and heavily permeated with specks of limonite. The labradorite crystals, although retaining their outlines, are almost completely converted to montmorillonite. Magnetite has partly altered to hematite. The walls of the vesicles have been deformed and pushed inward, apparently by the swelling of the rock through alteration. Photomicrograph taken in plane polarized light. Diameter of field about 3 mm.

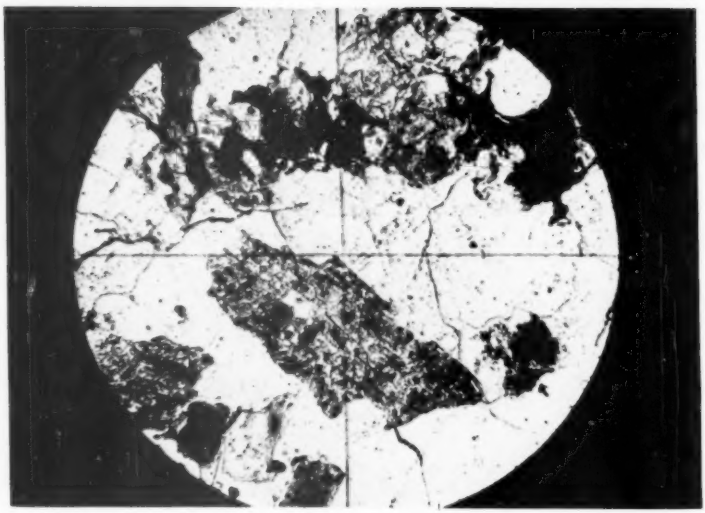

Figure 11. Photomicrograph of slightly weathered biotite granite (specimen 7) from an outer shell of a spheroidally weathered boulder. The white unaltered minerals are chiefly quartz and some microcline. The gray minerals, including the large crystal near the center, are oligoclase, which is deeply clouded with kaolinite and coated with large flakes of sericite (clear areas). The black grains are magnetite, and the dark gray mineral at the lower right edge of the photograph is biotite altering to chlorite. In the oligoclase of this section the flakes of sericite are larger and more abundant, and the kaolinization is more intense than in the oligoclase of the relatively fresh biotite granite (specimen 6) (photomicrograph not shown). Photomicrograph taken in plane polarized light. Diameter of field about 3 mm.

the results concluded that the "boulders of disintegration" were formed by the chemical weathering of the rock and its accompanying disintegration.

Summary of Current Views on Spheroidal Weathering

From the foregoing it is clear that most writers now consider spheroidal weathering to be caused by either of two processes: (1) the swelling and spalling of the exterior surface of angular blocks of rock due to the hydration, carbonation, and oxidation of constituent minerals in the outer surface, or (2) the swelling and spalling of the exterior surface of angular blocks which have been subjected to sudden, intense heating of their exterior by forest fires and brush fires.

The first process, which may take place in both humid and semi-arid climates, is the more common and operates not only at the surface of the ground but in some cases to a depth of 30 or 40 feet. The other process is undoubtedly local and confined to the surface of the ground since appreciable temperature changes by fires or by other means are not effective at depth. Accordingly, where spheroidal boulders are found forming at depth, it can be safely concluded that the process is one of hydration, carbonation, and oxidation of the minerals in the outer layers and not one of temperature changes. Spheroidal boulders lying on the surface may be the result of either of the two processes. Although it is assumed by many that such boulders located in semi-arid regions are the result of temperature changes, probably most have been caused by hydration, carbonation, and oxidation of minerals in the outer layers. Boulders of this type are well illustrated in Figures 5 and 6 and will be described later in this paper.

Microscopic Study of Spheroidally Weathered Boulders

General Statement

In the previous section it was concluded that the principal cause of spheroidal weathering is the expansion of the outer surface of a rock due to the hydration, carbonation, and oxidation of its mineral constituents. Although this explanation is now used by many writers, it is stated rather generally and vaguely without specific reference to the exact nature of the mineral changes. As far as the present writers are aware, no microscopic study has ever been made of spheroidal boulders

or the shells that surround them. Accordingly, it was deemed worthwhile to undertake a microscopic study of the boulders and surrounding shells in several typical examples of spheroidal weathering in order to determine the nature and intensity of mineral alterations.

Three rocks exhibiting particularly good spheroidal weathering were selected for study (figs. 1 to 6). One of these is a porphyritic olivine basalt from the northern end of the Koolau Range, Oahu, T. H.; the second, a vesicular basalt from the Schofield Plateau, near Wheeler Field, Oahu; and the third, a biotite granite from northern Colorado. In each case an especially good spheroid was chosen and a series of specimens was collected along a radius to represent the fresh rock of the boulder itself and the more weathered rock of the shells surrounding it. Thin sections were prepared from these specimens and mineral alterations were studied (figs. 7 to 11). Modes were determined with a Wentworth integrating stage and grain sizes measured with a micrometer ocular. Microscopic study of these specimens has enabled the writers to draw certain significant conclusions about the relationship of mineral alterations to spheroidal weathering.

PORPHYRITIC OLIVINE BASALT

General nature. This rock, belonging to the Koolau volcanic series, outcrops at the northern end of the Koolau Range, Oahu, about 3 miles southwest of the village of Kahuku. At this point about 1,000 feet above sea level, the lavas have been deeply dissected by streams, and one section is well exposed in a steep cut nearly 30 feet high where an old road follows a canyon wall. The basalt is so thoroughly weathered into spheroidal masses that the outcrop simulates a sedimentary deposit of rounded boulders (figs. 1 and 2). Spheroidal weathering extends from the surface to a depth of at least 30 feet.

The spheroids are lined up in more or less regular rows, arranged approximately vertically and horizontally, and individual spheres are spaced on centers ranging from 8 inches to 3 feet. At the contact between any two spheroids the line of demarcation is generally planar and suggests that a joint plane served as a starter. In many places the original joints are still visible. The spheroids themselves range from 6 inches

to 3 feet in diameter, and are larger and less weathered near the base of the cut. They are bounded by concentric shells which are concavo-convex with a maximum thickness near their centers ranging from half an inch to 3 inches, and which taper toward their edges.

The interior of the spheres is composed of fresh, firm rock consisting of a blue-green groundmass set with rounded, yellow-green phenocrysts of olivine. As one progresses from the fresh rock of the interior toward the outer shells, the groundmass becomes brownish yellow and eventually the olivine turns brown, loses its luster, and falls out of the specimen. The final weathering product surrounding the outer shells is a buff, brown, or red, friable rock which crumbles to a powder. The complete zone of alteration, i.e., from fresh rock to completely weathered material, takes place within a zone from 3 to 6 inches wide.

One particular spheroid, 2½ feet in diameter, was selected for microscopic study. The solid interior is 9 inches in radius and its rim of concentric shells is 6 inches thick (fig. 4). Three specimens were collected along the radius of the spheroid as follows: (1) fresh basalt (specimen 1) from the outer edge of the solid interior, 8 to 9 inches from the center; (2) slightly weathered basalt (specimen 2) from the innermost shell, 9 to 10 inches from the center; and (3) badly weathered basalt (specimen 3) from the outermost shell, 14 to 15 inches from the center.

Fresh basalt (specimen 1). This is a porphyritic rock consisting of a dense, light-gray groundmass set with abundant sub-rounded phenocrysts of yellow-green olivine. In thin section it was found to consist of sub-rounded, embayed phenocrysts of olivine and much smaller microphenocrysts of hypersthene, set in a dense groundmass of labradorite, augite, magnetite, and volcanic glass. Many of the olivine phenocrysts contain alteration rims of yellow-brown iddingsite averaging 0.4 mm. thick. The microphenocrysts of hypersthene have an average diameter of 0.22 mm. and all appear to have crystallized later than the olivine. The labradorite ($Ab_{40}An_{60}$) forms slender laths 0.1 mm. long which show random orientation except adjacent to olivine phenocrysts where they trend parallel to the borders. Small rounded grains of augite and magnetite are scattered among the labradorite,

and colorless, slightly birefringent volcanic glass fills the interstices between grains. The mode of this rock, in volume per cent, determined with an integrating stage, is shown in Table I together with the grain sizes of the constituent minerals.

TABLE I

Modes, in volume per cent, and grain sizes of porphyritic olivine basalt.

Minerals	*Modes*		*Grain Sizes*	
	Specimen 1	*Specimen 2*	*Range*	*Average*
Olivine	47.1%	46.9%	0.4–3.5 mm.	1.8 mm.
Hypersthene	8.7	9.5	0.1–0.3 "	0.2 "
Augite	15.8	16.9	(uniform)	0.02 "
Labradorite (ca. An_{50})	21.3	19.8	"	0.1 "
Magnetite	1.7	2.0	0.02–0.2 mm.	0.04 "
Glass	5.2	4.9	—	—
Miscellaneous	0.2	—	—	—
	100.0%	100.0%		

Except for slight serpentinization of some olivine phenocrysts along fractures, the rock is essentially unaltered. The labradorite, augite, and magnetite of the groundmass are quite fresh. The development of iddingsite rims is believed to be a late magmatic phenomenon.

Slightly weathered basalt (specimen 2). In this specimen the groundmass has turned light gray or buff and some of the olivine phenocrysts have lost their brilliant luster. The rock is less firm than specimen 1 and crumbles readily under a blow of the hammer. In thin section (fig. 7) this specimen is texturally similar to specimen 1 and its minerals are qualitatively similar (table I). The apparent small quantitative mineral differences between the two rocks are due partly to limitations in accuracy of the Rosiwal method and partly to actual original differences in the two specimens. The volcanic glass in specimen 2 is olive-green instead of colorless, possibly due to weathering. Tiny acicular microlites penetrate the glass.

This specimen shows slightly more alteration than specimen 1. All iddingsite rims about the olivine have been partly altered to limonite and have become nearly opaque. The olivine itself, however, remains relatively fresh as do the augite and magnetite of the groundmass. The centers of many labradorite

laths have been altered to a fine-grained aggregate with low birefringence which is believed to be montmorillonite, but the borders of the laths remain fresh.

Badly weathered basalt (specimen 3). In this specimen the groundmass has become yellow-brown. Although most olivine phenocrysts retain a high luster internally, their surfaces have turned dull and brown. These phenocrysts can be easily removed with the fingers and the rock can be crumbled in the hand. In thin section (fig. 8) the texture is found to be similar to that in the previous specimens and it is apparent that the original mode was also the same (table I).

This rock is highly altered. Iddingsite borders on the olivine phenocrysts are completely oxidized to limonite, but the olivine itself is still relatively fresh although slightly more serpentinized than in specimen 2. The major alteration has taken place in the groundmass. Augite crystals have been weathered and are now permeated with tiny grains of limonite which effectively obscure the crystals and prevent more thorough optical study. Labradorite crystals have been intensely altered throughout to a lamellar aggregate of montmorillonite, and only locally may the original laths be recognized. Most magnetite granules appear completely unaltered.

VESICULAR BASALT

General nature. This rock, a fine-grained, bluish gray, vesicular basalt of the Koolau volcanic series, is exposed in a deep road cut on the Schofield Plateau near the west gate of Wheeler Field, Oahu. The cut reveals spheroidal weathering of the basalt to a depth of 12 feet below the surface (fig. 3).

In general the spheroids are spaced on centers from 1 to 3 feet apart, but are not as well aligned as those in the porphyritic olivine basalt in the Koolau Range. The spacing of spheres and the arrangement of shells of adjacent spheres show clearly that the weathering began along joint planes. The shells are thinner than those in the basalt from the northern end of the Koolau Range. Generally they range in thickness from an eighth of an inch to 2 inches but the average is between a quarter and three-quarters of an inch. Furthermore, the thickness of an individual shell is more uniform throughout than in the porphyritic olivine basalt and the shell extends farther around the interior boulder; thus the shell

is less lenticular and the interior boulder is more completely surrounded by it.

The interior residual boulders are fresh and unjointed. The first apparent evidence of weathering is seen in the innermost shells that have maintained their texture but have turned grayish. In the outer shells the rock turns brown to yellow-brown and starts to fall apart. Surrounding the outer shells is a zone of brown or red-brown, completely decayed rock. The width of the weathered zone, i.e., from the fresh rock to the completely decayed rock, ranges from 6 to 12 inches.

Two specimens of this basalt were selected for microscopic study from one spheroidal mass, 2 feet in diameter: (1) relatively fresh basalt (specimen 4) from the periphery of the interior spheroid, 5 to 6 inches from its center; and (2) weathered basalt (specimen 5) from an outer shell surrounding the solid interior, 11 to 12 inches from its center.

Relatively fresh basalt (specimen 4). This specimen is medium gray, aphanitic, and contains abundant spherical vesicles averaging 1 mm. in diameter. Microscopically (fig. 9) its texture is intersertal, the rock consisting of a mat of labradorite laths (An_{64}) and augite and magnetite granules with colorless to brownish basaltic glass filling interstices. The labradorite is randomly oriented except adjacent to vesicles where the expanding gas bubbles forced the adjacent laths into a concentric arrangement. The labradorite shows albite twinning and conspicuous zoning. Augite and magnetite granules are scattered among the plagioclase. Many of the augite grains are long and slender like the labradorite, with an average length of 0.1 mm., but some are equidimensional with an average diameter of 0.04 mm. Irregular grains of reddish-brown iddingsite, developed from olivine, are scattered throughout the rock, and in some of these, cores of olivine still remain. A few microphenocrysts of hypersthene were noted. The mode of this rock and the grain sizes of its mineral constituents are shown in table II.

Although relatively fresh, this rock shows two effects of weathering. In the first place, many labradorite cores are altered to a very fine-grained birefringent aggregate which appears to consist of sericite, kaolinite, and epidote, although the positive identification of these minerals is not certain. In the second place, some augite crystals have become brownish by oxidation to limonite.

TABLE II.

Modes, in volume per cent, and grain sizes of vesicular basalt.

Minerals	*Modes*		*Grain Sizes*	
	Specimen 4	*Specimen 5*	*Range*	*Average*
Vesicles	23.0%	22.3%	0.3–2.1 mm.	1.1 mm.
Augite	22.6	24.1	0.02–0.2 "	0.1 "
Labradorite (An_{44})	33.5	47.9*	0.1–0.4 "	0.2 "
Glass	14.1		—	—
Magnetite	6.3	5.4	—	0.4 "
Olivine (altering to iddingsite)	0.5	0.3	0.04–0.3 mm.	0.1 "
Hypersthene	tr.	—	—	—
	100.0%	100.0%		

* The labradorite has been almost completely altered to montmorillonite. The ratio of montmorillonite to glass is difficult to determine.

Weathered basalt (specimen 5). The vesicular basalt from the outer shell of the weathered boulder has turned pinkish or yellowish and can be crumbled readily between the fingers. Under the microscope (fig. 10) it is texturally like the fresher material and its mode was probably originally about the same (table II). The rock has been conspicuously altered by weathering, however. Augite crystals are badly decomposed and have lost their birefringence, and many are now heavily permeated with specks of limonite. In some crystals serpentine appears to have developed but the clouded character makes this identification somewhat questionable. The labradorite crystals have been almost completely converted to lamellar aggregates of montmorillonite, and only locally do relics of the original mineral remain. In many places, however, the outlines of the laths are preserved. The volcanic glass can still be recognized but its ratio to montmorillonite is difficult to determine. Magnetite has partly altered to hematite.

The vesicles are not as smoothly circular as those in specimen 4. Practically all have been deformed and crystals of augite, altered labradorite, and magnetite have been pushed inward, forming irregular projections. It appears that the walls of the vesicles have been jammed inward by the swelling of the rock through alteration.

BIOTITE GRANITE

General nature. Many residual boulders of spheroidally weathered pre-Cambrian biotite granite lie upon the surface in

northern Colorado (figs. 5 and 6). One particularly fine example (fig. 6), along U. S. Highway 287 about 5 miles south of Virginia Dale, Colorado, was chosen for study. This boulder, approximately 3 feet in diameter, has a solid interior surrounded by from 5 to 10 concentric shells ranging in thickness from 1 to 4 inches. For the most part the shells have uniform thickness throughout and appear to have completely surrounded the interior sphere at one time.

The interior boulder is composed of pink, medium-grained, non-foliated granite, without joints. The rock in the shells is deeper pink and somewhat more crumbly, but is otherwise megascopically similar to the interior. Two specimens were selected from microscopic study from this spheroidal body: (1) relatively fresh granite (specimen 6) from the innermost shell, about 10 inches from the center of the spheroid; and (2) slightly weathered granite (specimen 7) from an outer shell, 6 to 8 inches outward radially from specimen 6.

Relatively fresh granite (specimen 6). This specimen, from the innermost shell of the weathered boulder, is a pink, medium-grained granite, relatively fresh and strong. Microscopically it is allotriomorphic and generally even-grained, although some portions tend to be seriate. One large perthite phenocryst 6.3 mm. long was seen. Perthite, microcline, oligoclase, quartz, and biotite are the essential constituents and magnetite is an accessory. Sericite and kaolin have formed from the feldspars. The mode of this specimen in volume per cent, together with the grain sizes of the modal minerals, is shown in table III.

TABLE III

Modes, in volume per cent, and grain sizes of biotite granite.

Minerals	*Modes*		*Grain Sizes*	
	Specimen 6	*Specimen 7*	*Range*	*Average*
Perthite and microcline	36.5%	41.0%	0.07–2.1 mm.	1.0 mm.
Oligoclase (An_{10-14})	23.1	25.2	" " "	" "
Quartz	31.1	24.6	" " "	" "
Biotite	6.2	4.7	—	0.7 "
Sericite	1.6	3.3	(see note below*)	
Magnetite	1.5	1.2	—	0.09 "
Apatite	—	tr.	—	—
	100.0%	100.0%		

* In specimen 6 this mineral ranges from tiny specks to flakes 0.4 mm. across, with an average diameter of 0.1 mm. In specimen 7 it ranges from tiny specks to flakes 0.6 mm. across, with an average diameter of 0.2 mm.

Perthite and microcline, in subhedral to anhedral crystals, comprise 36.5 per cent of this specimen, and twinned oligoclase (An_{12-14}), also subhedral to anhedral, makes up 23 per cent. The quartz grains, somewhat larger than the feldspars, are exceedingly irregular in outline and all are severely strained. Biotite, pleochroic in deep olive-green and yellow-brown, is scattered evenly throughout the rock. Primary magnetite is an inconspicuous accessory.

The minerals of this rock are slightly weathered. Perthite and microcline show meager kaolinization and sericitization, but oligoclase is conspicuously more altered and generally clouded with specks of kaolinite and flakes of sericite. The sericite ranges from tiny specks to large flakes 0.4 mm. in diameter, with an average diameter of 0.1 mm. It comprises 1.6 per cent of the granite. Some biotite has changed to chlorite with the concurrent separation of magnetite along cleavages, and some of this magnetite has weathered to hematite.

Slightly weathered granite (specimen 7). This specimen is from an outer shell and 6 to 8 inches outward radially from specimen 6. Megascopically it resembles closely specimen 6 except that it is slightly deeper pink as a result of more intense weathering. In thin section (fig. 11), specimen 7 is texturally nearly identical with specimen 6 but its mode differs somewhat. Perthite and microcline are greater by about 5 per cent but quartz is nearly 6 per cent less. The modes may be compared in Table III.

The most significant difference between this specimen and the preceding one lies in the intensity of alteration of the oligoclase. Nearly all grains are deeply clouded with kaolinite so that their twin lamellae are generally obscured, and flakes of sericite are both more abundant and larger. Reference to table III indicates that there is twice as much sericite in this rock as in specimen 6. This mineral ranges from tiny specks to flakes 0.6 mm. across, with an average diameter of 0.2 mm.

Significance of Microscopic Observations

Microscopic study of the spheroidal boulders described above leads to the following general conclusions regarding their development:

1. In general the cores of the spheroidally weathered boul-

ders consist of relatively fresh rock, but the shells surrounding the cores are more highly weathered. The intensity of this alteration increases outward more or less regularly through the successive shells. In the porphyritic olivine basalt, the interior boulder is fresh, but the inner shells are slightly weathered and the outer ones intensely so. The major alteration has occurred in the groundmass, the augite granules having partly oxidized to limonite, and the labradorite laths weathered to montmorillonite. Iddingsite rims around the olivine phenocrysts have also oxidized to limonite. Weathering of the vesicular basalt is even more marked. As one progresses from the fresh core outward, the augite crystals lose their birefringence, become clouded with specks of limonite, and locally seem to have altered to serpentine. Labradorite first shows alteration to sericite, kaolinite, and epidote on the periphery of the interior spheroid, and is finally converted to a fine aggregate of montmorillonite in the outer shells. Alteration of the biotite granite is less intense, but it is clear that the outer rims are more weathered than the inner ones. The chief changes are kaolinization and sericitization of the oligoclase. In the outer shells sericite is twice as abundant as in the inner ones and the flakes average twice the size.

2. In the weathering process, oxygen, water, and possibly some carbon dioxide were added to the rocks. New minerals, namely kaolinite, sericite, montmorillonite, serpentine, chlorite, hematite, and limonite were formed, most of these having specific gravities that are lower than those of the original minerals from which they altered. The result of these changes appears to have been an increase in the volume of the altered rock, the outermost shells suffering a more marked increase than the inner ones (fig. 4). Positive evidence of this increase is furnished by the outer layers of vesicular basalt in which the walls of the vesicles were apparently crowded inward by the increasing pressure. The amount of volume increase that took place in any of these rocks cannot be computed accurately, since the amount of material removed in solution is not known. Larsen (1948) found that the gruss surrounding spheroidally weathered boulders in Southern California, "has had some of its iron oxidized, has gained some water and much SiO_2 [leached from above], has lost a little K_2O, and gained a little Na_2O." (p. 119). Although these differences are small,

he concluded that they were adequate to expand the rock and cause it to crumble. He states: "A slight hydration of biotite and other minerals is probably sufficient to effect the change in volume that produces the disintegration and formation of the boulders." (p. 115). Leith and Mead (1915, p. 5-19) calculated that the weathering of a Georgia granite had caused a volume increase of 51 per cent, but since this rock was deeply decomposed, its volume increase must have been unusually large. The rocks discussed in the present paper probably suffered a much smaller increase, even in the outermost shells.

3. It appears probable that the spheroidal scaling of these rocks resulted from the oxidation and hydration of silicate minerals (fig. 4). In each case the fresh rock was first subdivided by joint planes into rectangular blocks, thus enabling subsurface water to attack each block from all sides. Weathering or alteration ensued along all faces of a block, and especially at edges and corners where the specific surface was greater. As a result, swelling of the outer surface of the block took place and internal stresses were set up. When these stresses had reached sufficient intensity, the rock split along a curved surface at a certain depth within the block where the cohesive strength of adjacent grains was exceeded. A concentric shell was thus produced. Further weathering along this new fracture produced additional shells within.

Spheroidal Boulders without Shells

Upon weathering some igneous rocks crumble to grains rather than scale off in shells, and the solid interior spheroid is bounded externally by a gruss of mineral fragments rather than by concentric shells. This is also spheroidal weathering. Whether a rock splits into shells or crumbles into grains appears to depend upon the cohesive strength between the mineral constituents of the rock. If this strength is great, adjacent grains will cohere, and, instead of crumbling, the rock will split along a curved surface at a certain depth within the boulder where the cohesive strength of the grains is exceeded by the shearing stress set up in the expanding outer portion. On the other hand, if cohesion is weak, due either to alteration along crystal boundaries or to the non-interlocking character of adjacent grains, the rock will crumble rather than separate as distinct shells. Fine-grained tough rocks,

such as basalts and diabases which have well-developed ophitic texture, generally have sufficient cohesion between grains to develop distinct shells upon weathering. Coarse-grained granites and basic rocks, however, whose grains are less firmly interlocked, generally crumble to a coarse angular gruss surrounding a spheroidal core.

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REVIEWS

Introduction to Historical Geology; by RAYMOND C. MOORE. Pp. 582, 364 figs. New York, 1949 (McGraw-Hill Book Co., Inc., $5.00).—This new textbook by Professor Moore, of the University of Kansas, is written for the elementary student who has had not more than one semester of geology. The first chapter is very helpful in that it brings together many isolated facts covered by the ordinary course in physical geology and shows how they are used in unraveling the past record of our planet. The problems of correlation, the geologic time scale, and the length of geologic time are also included. A thorough understanding of the contents of this chapter should do a lot towards preparing the student to appreciate the "Historical" approach to geology. The second chapter gives the background of evolutionary theory that is needed by one who has not studied biology. Chapter Three deals with the organization of the Solar system and a discussion of hypotheses that have been propounded to account for the origin of our planet. Beginning with Chapter Four, "The Pre-Cambrian Era," the book turns to a consideration of the interpretation of geologic history as shown by the rocks. This chapter and twelve that follow cover the usual material found in texts, to wit: distribution and character of formations, tectonics, vulcanism, economic products, and a little on the life of a particular period.

Chapter Twelve, "Nature and Evolution of Paleozoic Life," follows the chapter on the Permian and brings together in one place a mass of information, which in some books is scattered throughout the text. The wisdom of the plan used in this book may be questioned as students might wait until seven geologic periods have been studied before they come to a detailed description of some of the forms that lived during Cambrian time. Granted that it may be possible to give a more coherent description of Paleozoic life in a single chapter, nevertheless the reviewer wonders whether the student will get a clear picture of the life of each individual period. A possible solution to this problem would be to place this particular chapter ahead of the one on the Cambrian. A brief mention of the various forms of life would then be all that was necessary in each of the chapters on the Paleozoic. Similar chapters on Mesozoic and Cenozoic life follow the chapters on the Cretaceous and Quaternary. Changing their position in the text might also be considered. Chapter Twenty deals with "The Geologic Record of Man." An appendix of 28 pages, "Characters of Some Animal Groups Represented Among Fossils," closes the book. This appendix, which starts with the Protozoa and ends with the Amphibia, duplicates much that has been covered by the previous chapters

on the life of the various eras and contains some information that might well have been included earlier in the book. Thus a student studying the Ordovician, where graptolites are mentioned for the first time, must look them up in two other parts of the book to find out what they are like. Reorganization and consolidation of material might eliminate the need for the appendix.

As so often happens in first editions, there are numerous errors or doubtful statements that appear in the book. Some examples are given below. The letters under the illustrations of the fossils in Figure 139 do not agree with the descriptive text. On pages 149, 152, and 278, the author has placed the Eurypterids in the Crustaceans, although on page 511 they are correctly classified as Arachnida. Scorpions and spiders are also erroneously listed under Crustaceans on page 278 and correctly classified on page 511. If this was done in an attempt to simplify terminology, it is a dangerous policy. The statement (pages 127-129) that in the Ordovician "of the Appalachian geosyncline and the interior platform as far west as the Mississippi" the bentonite beds are "Commonly . . . one or two feet thick" gives a false impression, as a great percentage of these beds are measured in inches, not feet. An example of a sentence that can cause trouble for students is found on page 69. "The unfossiliferous Pre-Cambrian rocks differ broadly from Cambrian and younger formations in physical constitution and structure." No matter whether this is applied to igneous, sedimentary, or metamorphic rocks, it does not give the correct impression, for younger rocks of all three types can be cited that have been or could be confused with Pre-Cambrian rocks. There is nothing in physical constitution or structure that is typically Pre-Cambrian. Although most of the illustrations are excellent, there are a few that need to be replaced, as for instance, Figure 59, the title of which states that it "shows cliffs of Paleozoic strata lying nonconformably on tilted Pre-Cambrian formations." One can study this picture for a considerable time and still not be sure where the tilted Pre-Cambrian strata are to be found in it.

It is hoped that when a second edition of this book is printed most of the questionable portions will have been changed.

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PUBLICATIONS RECENTLY RECEIVED

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